Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

Efficiency of Distillation Columns Containing Packed Sieve Trays

Abu Bakr S. H. Salem[a]
[a] Chemical Engineering Department King, Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

To cite this Article Salem, Abu Bakr S. H.(1993) 'Efficiency of Distillation Columns Containing Packed Sieve Trays', Separation Science and Technology, 28: 13, 2255 — 2272
To link to this Article: DOI: 10.1080/01496399308016748
URL: http://dx.doi.org/10.1080/01496399308016748

SEPARATION SCIENCE AND TECHNOLOGY, **28**(13&14), pp. 2255–2272, 1993

Efficiency of Distillation Columns Containing Packed Sieve Trays

ABU BAKR S. H. SALEM
CHEMICAL ENGINEERING DEPARTMENT
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN 31261, SAUDI ARABIA

ABSTRACT

The Murphree efficiency of the fifth tray in a six-sieve tray distillation column, 7.8 cm in diameter and 85 cm high, was increased from 37.5 to 90% when three disks of a wire mesh pad, 9 cm high, were placed on the tray. An acetone–methanol test system was used in this investigation. The pressure drop across the tower corresponding to this packing increased by 33%. Nine disks of Raschig rings of similar height increased the tray efficiency to 75% and the pressure drop by 16%. A model was used for the azeotropic system, and the overall tower efficiency was found to increase by about 20% due to the presence of packing on a single tray.

INTRODUCTION

Tray towers are the most common type of distillation equipment. The details of the tray layout must be selected so as to ensure a reasonable pressure drop and avoid flooding, excessive weeping, and entrainment. The most commonly used types of trays are bubble cap, valve, and sieve.

Sieve trays find widespread use in many distillation applications. They are much simpler in construction than bubble-cap and valve trays since their fabrication requires only the formation of small holes in the tray. These perforated trays will continue to be used because they are inexpensive, easily fabricated, and have performed well in many applications. The liquid flows across the tray and down the downcomer. Contact on a sieve tray, as in a valve tray, is between vapor rising through orifices and the liquid moving across the tray.

In sieve tray columns the vapor is dispersed through the openings of the tray into the liquid held on it by the pressure of the vapor. Excessive vapor flow rates can lead to flooding and entrainment problems. On the

other hand, lower vapor flow rates can lead to weeping, showering, or dumping effects. Such malfunctions greatly reduce mass transfer tray efficiencies.

While distillation is carried out in a stagewise manner in tray towers, in packed columns the process is continuous. The function of packing is to promote fluid turbulence and mass transfer by providing a tortuous gas flow path through the liquid which, ideally, flows as a film over the surface of the packing and as droplets between and within the pieces of packing. At times the liquid may tend to flow down the wall, bypassing the vapor flowing up the middle of the tower. At very low flow rates, there may be insufficient liquid to wet the surface of the packing. Channeling and flooding also restrict the range of operability in packed columns.

The advantages of both packed and tray columns may be combined by placing packing on the trays in a tray tower. Spagnolo and Chuang (1) reported an increase of 3–20% in sieve tray column efficiency when a 25-mm thick bed of knitted mesh packing was placed on the trays of the tower. The test column was 0.311 m in diameter and consisted of three sieve trays spaced 0.381 m apart. They also reported that packing reduced entrainment by 30% at low gas flows and 85% at high flows. Estimating the equivalent Sauter-mean bubble diameters from efficiency and hydraulic data, they concluded that packing resulted in an increase of 2.5 times in interfacial area.

Salem and Alsaygh (2) examined the effect of using deeper beds of Raschig rings on selected plates of a six-sieve tray column, 7.8 cm in diameter and 85 cm high. A methanol–water system was used in that study. Glass rings were then randomly placed on five of the six trays of the column. The top plate was not packed since reflux was introduced through it. Other packing locations with stainless steel rings were also used. Packing placed on the five trays of the column lowered the degree of separation by about 12%. This contradicts the findings of Spagnolo and Chuang (1). Lower percentage recovery has been obtained when the feed was introduced on the packed tray. This may be explained by the possibility of downcomer backup when the reflux and the liquid part of the feed have to go down together through the packing. However, stacked stainless steel packing, 11.5 cm high, placed on the fifth plate alone increased the separation degree by about 75%. The same degree of separation has been also achieved by placing 20 cm random glass rings on plates 4 and 5. The optimum feed plate was that just below the packed tray.

Chen et al. (3) also used the methanol–water system to study the hydraulic and mass transfer performance of a combined knitted mesh packing and sieve tray. Their findings supported those obtained by Salem and Alsaygh (2). They found that placing the packing on a sieve tray in a tower

of 0.15 m diameter increased its Murphree efficiency by 40–50% and the pressure drop by 20%.

However, Dribika and Biddulph (4) reported that tray efficiencies using the methanol–water system are markedly increased due to surface tension effects. This effect is related to the Marangoni index. The effect of surface tension gradients on efficiencies was found to be a combination of surface renewal effects in the lower composition range, enhancing the mass-transfer coefficients, and increasing interfacial area with increasing composition at the higher composition region.

Therefore, systems having positive surface tension effects, such as the methanol–water system (the surface tensions of methanol and water are 19 and 61 dyne/cm, respectively), most probably enhance mass transfer rates and increase tray efficiencies. This warrants using a system of neutral or negative surface tension to eliminate or alleviate this parameter when studying the effect of placing packing on sieve tray performance.

The objective of the present work is therefore to investigate the effect of using different types of stacked packing on the efficiency of a sieve tray column by using a neutral surface tension system. The acetone–methanol system was used in this study. The difference between the surface tension of these components is small (the surface tension of acetone is about 16 dyne/cm). Therefore, it can be assumed to be a neutral system. However, this system is abnormal because it has a minimum azeotropic composition of 0.769 mole fraction acetone boiling at 54.7°C (5).

EXPERIMENTAL WORK

Apparatus

The distillation system used is shown schematically in Fig. 1. The system consists of a stainless-steel feed reservoir of approximately 40 L capacity, a pump for transferring the feed from this reservoir to a cylindrical well-insulated stainless-steel boiler having a capacity of 20 L, and a 85 cm high, 7.8 cm i.d. plate column with six sieve plate sections. The bottom section is bolted at its bottom to the reboiler, and the top section is connected to the vapor feed line by a bell reducing coupling section and a flexible Teflon expansion joint. These sections were initially assembled from a 12.5 cm long, 7.8 cm i.d. Pyrex pipe section and a stainless steel process ring 2.5 cm high which holds the sieve tray. The tray is a stainless-steel plate 2 mm thick and 7.5 cm in diameter. The active area of the tray contains 36 holes of 3 mm diameter each. Tray spacing is about 15 cm. A stainless-steel vertical pipe with a 10-mm diameter opening acts as the downcomer. A smaller size stainless-steel pipe, fitted inside the down-

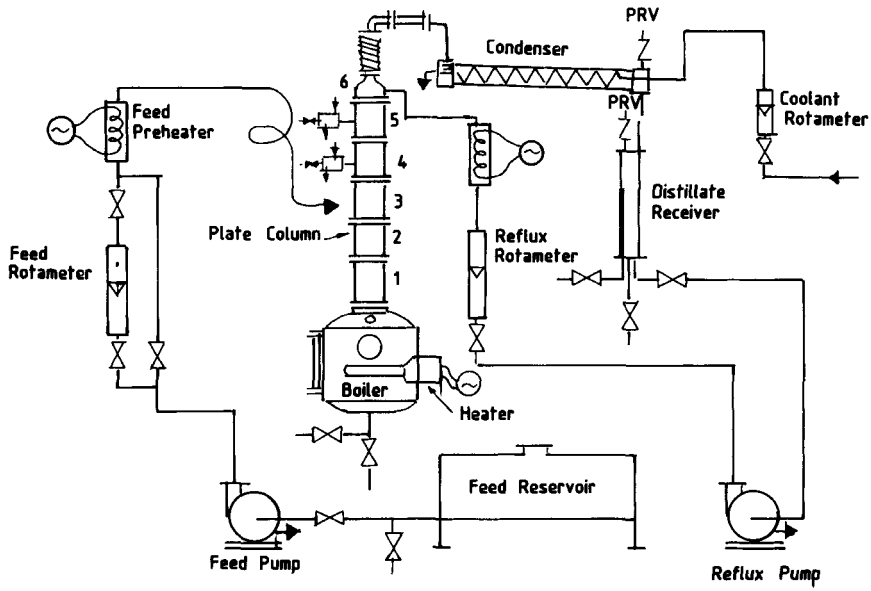

FIG. 1 Schematic flow diagram for the distillation column.

comer by screws, functions as the weir. Therefore, the weir height can be adjusted from 6 to 36 mm to control the liquid level above the tray.

The process ring holding the tray is provided with appropriate rubberized asbestos gasketed flanges and bolts and process fittings for feed, pressure, and temperature measurements, liquid sampling, and weir-downcomer adjustment. Pressure can be measured by a water-filled manometer. The temperature at each plate and at other points in the apparatus is measured by thermocouples of the chromel–alumel type. Each thermocouple is epoxy-sealed within a stainless-steel tube. The sensor ends of the thermocouples of the trays are pointed in a downward direction inside the weir, approximately 6 mm above the tray. The thermocouples are remotely connected to a multiposition thermocouple selector which contains two jacks for analog read-out signals. The jacks are connected to a digital indicator which can show a thermocouple reading at a time. Two of the glass column sections, Sections 4 and 5, were replaced by similar stainless-steel sections in order to supply them with vapor samplers from the corresponding plates. Each sampler was a double pipe condenser. The inner pipe was 7 cm long and 1.4 cm in diameter. The outer pipe had a diameter of 3.2 cm. The inner pipe intake was provided with a wire pad to reduce entrainment of the splashed liquid. Figure 2 is a photograph of the stainless-steel sections and the condensers connected

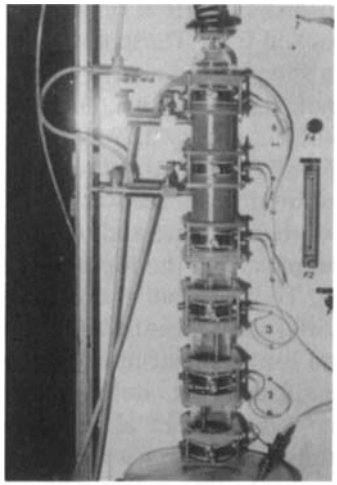

FIG. 2 The distillation column fitted with the metal sections and the vapor samplers.

to the column. A certain volume of vapor sample was allowed to enter the sampler and entrapped there. The sampler was cooled for a certain period to allow for the vapor to be condensed and then collected as liquid; the concentration of the more volatile material in this sample was then measured by refractometry.

The column was provided with a heat exchanger fitted with a rotameter for monitoring coolant flow and a pressure relief valve set at 1.0 psig. A 7.5-cm o.d., 30 cm long Pyrex glass distillate receiver fitted with a pressure relief valve received the liquid product from the condenser. Two preheaters are included in the feed and reflux lines.

Two rotameters (0–100% scale) were used for measuring the feed and reflux rates.

The packing materials used were stainless-steel (SS) Raschig rings and disks of SS wire pad. The rings were 10 mm o.d., 10 mm high each. They were stacked in an orderly fashion and held in place within a larger SS ring of the same height as the Raschig rings and of a diameter equal to the inside column diameter.

The wire mesh pad disks were made of SS wire pad 6 mesh/cm^2. Each disk was 30 mm high and was fabricated with the same diameter as the inside column diameter. The disks and the large rings containing the Raschig rings were provided with an opening 16 mm in diameter to accommodate the downcomer. In this manner, layers of stacked Raschig rings or disks of wire packs could be placed on selected trays in the column.

Two or three wire pad disks and five or nine Raschig ring layers were used on the selected packed tray. These packing materials and their configuration are shown in Fig. 3.

The acetone–methanol system was used in this investigation. Methanol of 99.5% purity (bp 64–65°C, density 0.79 kg/L) and acetone of 99% purity (bp 56°C, density 0.785 kg/L) were mixed to form a solution of 0.36 mole fraction acetone. The solution was used as feed in all runs.

The concentrations of the distillate and the bottom products as well as the liquid and vapor samples from the top plates were measured by using an Abbé refractometer. To carry out these measurements, solutions of acetone–methanol in different concentrations were made and calibration curves were determined for this instrument.

The vapor–liquid equilibrium data determined by Othmer for this system was obtained from Prausnitz et al. (5). Their van Laar equations developed for correlating this system were used in the data analyses of this work.

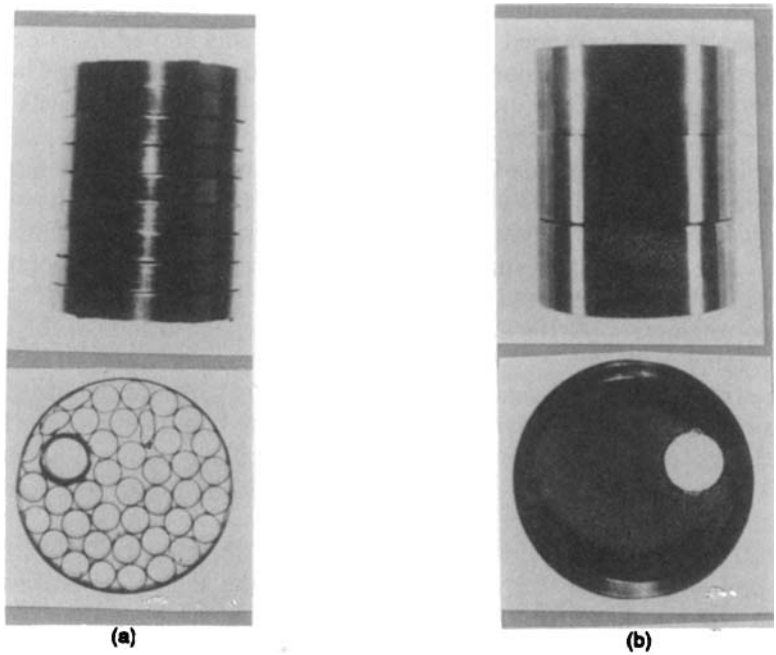

FIG. 3 (a) Stainless steel Raschig rings layers. (b) Stainless steel wire mesh pad layers.

Experimental Procedures

The acetone–methanol solutions were prepared a day before the experiment. They were well mixed and placed in the feed reservoir.

Before the experiments were started, the column was dismantled, thoroughly cleaned, and reassembled. The weir height was adjusted and kept at about 6 mm above the plate in all runs. The column was first operated without packing and then with different types of packing. Salem and Alsaygh (2) found that placing packing on the plate just below the reflux plate has resulted in the highest increase of the degree of separation of the system used. Therefore, in this present study the packing rings or disks were only placed on the fifth tray. Reflux was introduced on the sixth tray in the tower used.

At the beginning of each experiment the feed pump was switched on and the feed was introduced to the column until the boiler was three-quarters full. The feed was then stopped and the boiler was heated until the vapor reached the overhead condenser. Cooling water was run through this condenser. The condensed distillate was received in the accumulator. At this point the feed pump was switched on again to compensate for the boiloff rate. The reflux pump was also switched on. The reflux rate was adjusted at 33 mL/min to keep a constant liquid level in the accumulator. This rate was kept constant throughout these experiments. The boiler and plate temperatures were recorded every 5 minutes. The steady-state temperature profile was attained 25 minutes after starting.

When the boiler was again three-quarters full under operating conditions, the feed pump was switched off. From this point, the system was operated at total reflux. The column reached the new steady-state conditions within 2–3 minutes.

The pressure drop across some of the trays was measured with a manometer in some of the experimental runs. Liquid samples from each plate were collected through the sampling ports. Vapor samples from Plates 4 and 5 were collected as liquids from the vapor samplers. Only a few drops were collected in order not to disturb the system's steady-state conditions. Vapor coming out of Plate 6 was received in the accumulator from the overhead condenser and sampled. For each experiment, samples were collected from the distillate and bottom products. The samples were then analyzed for acetone concentration by using refractometry.

RESULTS AND DISCUSSION

The performance of the tower was evaluated when the fifth plate was unpacked or packed with the two types of packing with different heights.

TABLE 1
Column Plate Compositon (mole fraction) Profile under Total Reflux. Charge: Methanol–Acetone (X_f = 0.36 mole fraction). Analytical Method: Refractive Index (R.I.) at 25°C

				Plate number											
				4				5				6			
		Reboiler		Vapor		Liquid		Vapor		Liquid		Vapor		Liquid	
No.	Packing[a]	R.I.	X_B	R.I.	y	R.I.	x	R.I.	y	R.I.	x	R.I.	y	R.I.	x
1	None	1.3441	0.27	1.351	0.47	1.3504	0.45	1.3518	0.50	1.351	0.47	1.353	0.58	1.351	0.50
2	R.R. 5 Disks	1.3432	0.25	1.3518	0.5	1.351	0.47	1.353	0.58	1.3518	0.50	1.354	0.6	1.353	0.58
3	R.R. 9 Disks	1.343	0.24	1.3528	0.54	1.3518	0.50	1.354	0.60	1.353	0.58	1.3550	0.64	1.354	0.60
4	WMP 2 Disks	1.3423	0.23	1.354	0.60	1.353	0.55	1.3549	0.64	1.354	0.60	1.3559	0.69	1.3558	0.68
5	WMP 3 Disks	1.3418	0.22	1.355	0.65	1.3544	0.62	1.3560	0.70	1.3558	0.676	1.3560	0.70	1.3559	0.69

[a] R.R. = Raschig rings. WMP = wire mesh pad.

Running the tower with the unpacked tray served as a reference for the other conditions. Table 1 shows the concentration of the vapor and liquid streams in the three top plates and the bottom stream composition. This table indicates a large improvement in the purity of the top and bottom streams. The distillate and bottom products' purity has increased by about 31 and 18.5%, respectively, when using the three disks of wire mesh pad packing.

Table 2 shows the effect of placing packing on the fifth plate on the pressure drop of this plate and on the whole column. Placing the three wire pad disks resulted in 100 and 33% increases in the pressure drop through the plate and the column, respectively.

Murphree Tray Efficiencies

The Murphree tray efficiencies have been calculated using the following equations:

$$E_{Mv} = \frac{y_n - y_{n-1}}{y_n^* - y_{n-1}} \tag{1}$$

$$E_{Ml} = \frac{x_n - x_{n+1}}{x_n^* - x_{n+1}} \tag{2}$$

where E_{Mv} and E_{Ml} are the Murphree efficiencies for the vapor and liquid phases of tray n, respectively

y_{n-1}, y_n = vapor compositions to and from tray n

x_{n+1}, x_n = liquid compositions to and from tray n

y_n^* = composition of the vapor in equilibrium with the liquid on the tray n, x_n, where $y_n^* = k_n x_n$

TABLE 2
Effect of Packing on Plate and Column Pressure Drop

Type of packing	Pressure drop (inches of water)		Percentage increase in pressure drop	
	Across Plate 5	In the tower	Across Plate 5	In the tower
None	2.00	6.0	—	—
5 Raschig ring disks	2.50	6.5	25.0	8.0
9 Raschig ring disks	2.75	7.0	37.0	16.0
2 Wire pad disks	3.50	7.5	75.0	25.0
3 Wire pad disks	4.00	8.0	100.0	33.0

x_n^* = composition of the liquid in equilibrium with the vapor of tray n, y_n, where $x_n^* = y_n/k_n$
k_n = distribution ratio of tray n

The results of the efficiency calculations are given in Table 3. Some of these data are plotted in Fig. 4. The table shows large improvement in the efficiencies of both phases in the case of locating the packing on the tray. The table and the figure indicate that the efficiency of the liquid phase is usually lower than that of the vapor phase. The vapor phase can attain a homogeneous concentration faster than does the liquid phase due to its fast diffusion and mixing within the phase. If equilibrium is attained, liquid phase efficiencies should be equal to those of the vapor phase. However, due to imperfect mixing of the liquid on the plate, the point efficiencies may not be the same. Also, equilibrium conditions cannot be assured on the actual plates.

Figure 4 indicates that the plate with 9 cm mesh pad packing produced

TABLE 3
Selected Plate Vapor and Liquid Murphree Efficiencies for Different Types of Packing

Packing	4		5		6	
	E_{Mv}	E_{Ml}	E_{Mv}	E_{Ml}	E_{Mv}	E_{Ml}
None	—	0.21	0.375	0.30	0.625	0.50
5 Raschig ring disks	—	0.30	0.625	0.50	0.710	0.66
9 Raschig ring disks	—	0.42	0.75	0.58	0.80	0.72
2 Wire pad disks	—	0.67	0.80	0.79	0.86	0.83
3 Wire pad disks	—	0.73	0.90	0.875	0.95	0.937

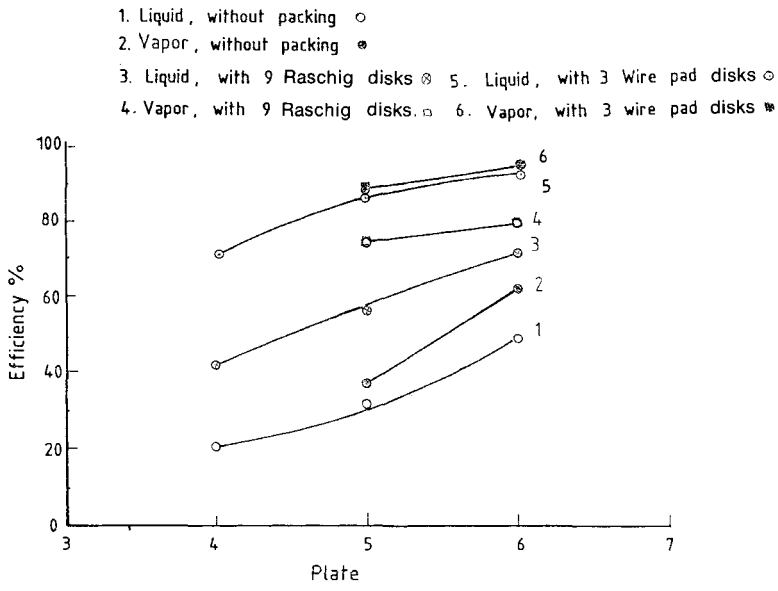

FIG. 4 Plate vapor and liquid efficiencies with or without packing.

almost identical efficiencies in both phases where the deviation from a perfect plate is relatively small.

The high increase in the efficiency obtained in this study can be attributed only to the presence of packing on the tray. Any other effects, such as surface tension gradients, may not have any role in such an efficiency increase since the acetone–methanol system used is almost neutral.

The large increase in tray efficiency in the case of wire mesh pad packing may be attributed to the fact that the mesh is more effective in breaking up the vapor bubbles before they are fully grown at the orifices of the sieve tray. The mesh may also be effective in generating a uniform distribution of stable bubbles in the froth, and this should result in a higher interfacial area and longer residence time. The mesh packing may also be more effective in reducing backmixing which gives rise to a much improved tray efficiency. With a conventional tray, the liquid is assumed to be completely mixed in the vertical direction due to the intense agitation in the froth. The presence of packing on the tray offers resistance to liquid flow, possibly leading to a concentration gradient. In addition, mesh packing can largely improve the liquid distribution—and it reduces the weeping and entrainment of the tray. It can also be assumed that mesh

packing can lead to turndown ratios of about 20% more than that for a conventional sieve tray (3).

However, increased tray efficiency and capacity can lead to reduced column heights.

Data Analysis

The model used for the analysis of data obtained in this investigation is based on an algorithm developed by Tierney and Abdelmalek (6) for calculating the compositions and temperatures in the distillation of a multicomponent system operating at total reflux conditions. This algorithm is based essentially on the well-known equations of Fenske and Underwood. Since the compositions of passing streams in the case of total reflux must be the same,

$$y_{i,n} = x_{i,n-1} \tag{3}$$

where $y_{i,n}$ is the mole fraction of component i in the vapor of a multicomponent system of stage n, and $x_{i,n-1}$ is the mole fraction of component i in the liquid phase of stage $n - 1$. The stages are numbered from 1 (the condenser) to n (the reboiler). Assuming equilibrium in each stage,

$$y_{i,n} = k_{i,n}x_{i,n} \tag{4}$$

where $k_{i,n}$ is the equilibrium ratio for component i in stage n. Equations (3) and (4) can be written for all stages from 1 to n and then combined to give a relation between the distillate and bottoms compositions of component i:

$$x_{i,1} = (k_{i,2} \cdot k_{i,3} \cdot k_{i,4} \cdots k_{i,n})x_{i,n} \tag{5}$$

If component j is defined as the reference component, then the ratio of the compositions in stage 1 is given by

$$x_{i,1}/x_{j,1} = (\alpha_{i,2}\ \alpha_{i,3}\ \alpha_{i,4} \cdots \alpha_{i,n})(x_{i,n})/(x_{j,n}) \tag{6}$$

where

$$\alpha_{i,n} = (k_{i,n})/(k_{j,n}) \tag{7}$$

α is defined as the relative volatility of component i referred to component j. The mole fractions in each stage must also sum to 1.0:

$$\sum_{1}^{m} x_{i,n} = 1, \qquad n = 1, \ldots, N, \qquad m = \text{number of components} \tag{8}$$

These equations apply for any system operating at total reflux. An overall material balance equation based on 1 mole of feed can be written for each

component:

$$f_i = rx_{i,1} + (1 - r)x_{i,n} \tag{9}$$

where f_i is the mole fraction of component i in the feed, and r is the moles of distillate per mole of feed defined as the distillate fraction.

Equation (6) obviously applies for any finite reflux ratio, no matter how large. Total reflux can be considered as the limit obtained by letting the reflux ratio become very large, and Eq. (9) then provides a very useful relation between the distillate and bottoms compositions.

For a fixed feed composition, fixed distillate fraction, and a fixed number of stages, there is a unique solution to the above equations.

The major computational difficulty in solving Eqs. (3) through (9) is the nonideal behavior of the system and that the distillate fraction is unknown. The nonideal behavior of the system results in varying equilibrium ratios with different liquid compositions as well as of temperatures. Hence, in this case a calculation procedure using the known bottoms liquid composition can be used. The activity coefficient can be calculated, and the bubble point of the liquid determined. Simultaneously, the equilibrium vapor composition is also determined. This is, by Eq. (3), equal to the liquid composition in stage $(n - 1)$.

This calculation step is repeated for each stage until stage 1 is reached. The overall material balance, Eq. (9), is now used to determine the value of r, the moles of distillate per mole of feed.

Data obtained for case 5 in Table 1 where 3 disks of wire mesh pad were placed on the tray were analyzed by this model. Starting from the bottoms composition $x_B = 0.2$, the bubble point for the bottom tray was calculated using the van Laar activity coefficients correlations for the acetone–methanol system. The equilibrium vapor composition was also determined. Hence, the liquid composition of the plate above is determined according to Eq. (3). The calculations were repeated until the top plate was reached. The results of this calculation are given in Table 4. The deviation between the calculated and experimental values were found to be less than 6%. Deviation in the r value was about 3%.

Such a deviation may be attributed to experimental measurement errors or to disturbances in the reflux flow rate to the system. It should be mentioned here that this flow rate was manually controlled. However, such a range of deviations can be tolerated.

Modeling of the Binary Azeotrope

The basic problem with azeotropic distillation design is that the relative volatility of the mixture is not constant, hence the explicit y–x relation,

$$y = (\alpha x)/[(1 + (\alpha - 1)]x \tag{10}$$

TABLE 4
Data Analysis Using Total Reflux Model[a]

Plate no.	Starting x_B, mole fraction	Bubble point, °C	$y_{calc.}$, mole fraction	$y_{meas.}$, mole fraction	$x_{calc.}$, mole fraction	$x_{meas.}$, mole fraction	% Deviatiion in x	% Deviatiion in y
Reboiler	0.22	58.20	0.385	—	—	—		
2		56.15	0.515	—	0.385	—		
3		55.30	0.585	—	0.515	—		
4		55.10	0.645	0.65	0.585	0.620	5.8	0.70
5		55.00	0.675	0.69	0.645	0.676	4.6	−2.20
6		54.95	0.695	0.70	0.675	0.69	2.2	0.70

[a] $\%\ \text{Deviation} = \dfrac{\text{calculated value} - \text{measured value}}{\text{calculated value}} \times 100.$

does not apply. It follows, therefore, that the usual design models, such as the Fenske–Underwood equations, are invalid for azeotropic distillation. However, Anderson and Doherty (7) developed a simple y–x relation for binary azeotropic mixtures which can be applied to the design of columns treating such mixtures. The basic idea introduced is to recognize that an azeotropic point acts as an impassable barrier which the column composition profile cannot extend beyond. Instead of attempting to fit an equation to the entire vapor–liquid equilibrium curve, this model divides the curve into two sections at the azeotropic composition. Each section is then a perfectly adequate representation of the vapor–liquid equilibrium prevailing in an azeotropic column lying within its jurisdiction. Each section can then be considered to be a separate system, with the azeotropic composition treated as a pure component for each. A coordinate transformation in each of the two portions of the curve enables one to represent the two sections, or at least the section of interest, in a constant relative volatility-like fashion.

Therefore, for the first section for example, two new composition variables x' and y', which vary from 0 to 1 (at the azeotrope), are introduced where

$$x' = x/x_{az} \tag{11}$$

$$y' = y/y_{az} \tag{12}$$

where $x_{az} = y_{az}$ = the composition at the azeotrope. Equation (10) can then be written in terms of the new variables x' and y'. The value of the relative volatility α can then be estimated from the vapor–liquid experimental data by using the most accurate, and most involved, nonlinear regression procedure.

To perform the nonlinear regression, let residual R_e be defined as

$$R_e = \sum_i^P (y'_{\text{meas.}} - y'_{\text{calc.}})^2 \tag{13}$$

$$= \sum_i^P \left(y' - \frac{\alpha x'}{1 + (\alpha - 1)x'} \right)^2 \tag{14}$$

where P is the number of experimental data points.

The objective is to find the value of α which minimizes the sum of the squares of the residuals R_e. This is easily accomplished by finding the value of α which solves

$$dR_e/d\alpha = 0 \tag{15}$$

Once the value of α is calculated, it is possible now to apply the Fenske equation to estimate the minimum number of trays $N_{\min}$ at total reflux conditions and the Underwood equation to calculate the minimum reflux ratio $R_{\min}$ by using the experimental data as follows:

$$N_{\min} + 1 = \frac{\ln \left[\frac{x'_D}{1 - x'_D} \cdot \frac{1 - x'_B}{x'_B} \right]}{\ln \alpha} \tag{16}$$

$$R_{\min} = \frac{1}{\alpha - 1} \left[\frac{x'_D}{x'_F} - \frac{\alpha(1 - x'_D)}{(1 - x'_F)} \right] \tag{17}$$

for a saturated liquid feed where B, D, and F stand for the bottom, distillate, and feed, respectively.

This model has been applied to the acetone–methanol system used in this investigation. The system pressure was constant at ambient, and the minimum boiling azeotrope occurs at 54.7°C and $x_{az} = y_{az} = 0.769$ mole fraction (5). The value of α was 2.86 for the section of interest from zero to the azeotrope.

The minimum number of plates and minimum reflux ratios have been calculated for the unpacked tray and for the different types of packing.

The theoretical number of trays N has been also calculated by the Harg (8) correlation:

$$N = (N_{\min} + Y)/(1 - Y) \tag{18}$$

where

$$Y = 1 - X^{1/3} \tag{19}$$

$$X = (R - R_{\min})/(R + 1) \tag{20}$$

$$R = aR_{\min} \tag{21}$$

$$a = \text{factor} = 1.1\text{–}1.5$$

assuming that $a = 1.5$, the value of N was calculated for each case. The column efficiency, E_{0c} was estimated by

$$E_{0c} = N/N_{\text{act}} \tag{22}$$

where N_{act} = the actual number of plates, which was 6.

The results of this calculation are given in Table 5. The results indicate that about a 20% increase in the overall column efficiency has been obtained due to placing three disks of wire mesh packing on the top plate. These results indicate the azeotropic model may be considered a suitable tool for analyzing such systems.

Comparison of Mesh and Raschig Rings Packings

The results obtained and presented in Tables 3 and 5 show that wire mesh packing was more effective in increasing tray and column efficiencies than were Raschig rings. This may be attributed to the fact that mesh packing offers a larger surface area of contact to fluids than do Raschig rings. However, the height of the mesh packing, 9 cm, increased the pressure drop by 100% compared to a 33% increase in the case of Raschig rings, as shown in Table 2.

The total tray pressure drop is the sum of the head required to drive gas through the aerated liquid and the packing voids on the tray. The packing contribution to pressure drop may have become larger in the case of using wire mesh pad because the effective whole area was reduced to a larger extent than what occurred in the case of using Raschig rings as packing. Therefore, it is important to determine the extra pressure drops caused by the packing used, so that one can properly design the packed tray to meet the process requirements. The use of a larger hole area may be effective in reducing the packing extra pressure drop.

TABLE 5
Summary of the Design Calculation Using the Binary Azeotropic Model

Run	x_D	x_B	$\acute{x}_D$	$\acute{x}_B$	$N_{\min}$	$R_{\min}$	N	E_{0c}
1	0.58	0.27	0.754	0.351	0.6508	0.1550	3.150	52.5
2	0.60	0.25	0.780	0.325	0.901	0.2607	3.185	53.1
3	0.64	0.24	0.832	0.312	1.276	0.4708	3.405	56.7
4	0.69	0.23	0.897	0.103	1.873	0.7335	4.140	69.0
5	0.70	0.22	0.910	0.098	1.984	0.786	4.282	71.4

Table 3 shows that not only has the performance of the packed tray (tray 5) increased, but that of the trays above and below it has also improved. This may be explained by realizing that trays in a tower are not separate discrete units. Each plate is affected by the adjacent plates since the same fluids are flowing up and down through these plates. In the presence of packing, the liquid flowing down from tray 5 will be richer in the less volatile component due to the more efficient mass transfer provided by the packing. Such a liquid will be more capable of depriving the vapor of tray 4 of its heavy component contents, with a consequent increase of this tray's efficiency and the efficiencies of the trays below.

The same rationale can be used to explain the increase in efficiency of plate 6 when packing was placed on plate 5. In this case the vapor from plate 5 flowing to plate 6 is richer in the more volatile component than in the case of a bare tray. Hence, the concentration of the vapor produced from plate 6 will be relatively richer in the more volatile component.

However, the increase in efficiency in the tray below the packed tray was more pronounced than in the tray above. This may be due to the more efficient distribution of the liquid flowing from the packed tray to the tray below than in the distribution of the reflux on tray 6.

CONCLUSIONS

The conclusions drawn from this investigation can be summarized as follows.

1. Large increases in sieve plates and tower efficiencies can be obtained when stacked packing is placed on the tray below that receiving the reflux in the tower. Such efficiency increases can be attributed to the efficient distribution of the reflux on the tower plates and the larger contact area between rising vapor and descending liquid caused by the packing. An increase in the efficiency of the tray columns can result in the use of shorter towers.
2. For positive surface tension systems, the increase in tray efficiencies may be relatively higher than for other systems treated in packed sieve tray towers due to the surface tension effects.
3. The cheaper Raschig ring packing produced an increase of about 8% in tower efficiency compared with 36% obtained when using the most expensive wire pad of the same height.
4. The tower pressure drop increased by 33% because of the existence of packing. This can be accommodated by correspondingly increasing the heat input to the reboiler. A comparison between the increase in cost of fuel and the increase in product purity obtained has to be made in order to reach a proper conclusion. A different way of accommodating this

increase in pressure drop may be to enlarge the diameter of the openings of the plate.

NOMENCLATURE

a	factor = 1.1–1.5
D	distillate flow rate (mol/h)
E_{Ml}, E_{Mv}	Murphree efficiency of liquid and vapor phases, respectively
E_{0c}	column efficiency
f_i	mole fraction of component i in the feed
k	equilibrium ratio
N	number of theoretical trays
P	number of experimental data points
R	reflux ratio
R_e	residual error
R.I.	refractive index
R.R.	Raschig rings
r	moles of distillate per mole of feed
SS	stainless steel
W.M.P.	wire mesh pad
X	parameter defined by Eq. (20)
x	liquid phase concentration, mole fraction
x'	liquid phase concentration defined by Eq. (11)
x^*	liquid phase concentration in equilibrium with a certain vapor concentration, mole fraction
Y	parameter defined by Eq. (19)
y	vapor phase concentration, mole fraction
y'	vapor phase concentration defined by Eq. (12)
y^*	vapor phase concentration in equilibrium with a certain liquid concentration, mole fraction
α	relative volatility

Subscripts

0	no packing
1, 2	components
act	actual
av	average
az	azeotrope
B	bottom
D	distillate
F	feed

min	minimum
n	tray number
i, j	components

ACKNOWLEDGMENT

This work is based on the experimental results obtained by Abdallah Al Marri through his final year project.

REFERENCES

1. D. A. Spagnolo and K. T. Chuang, "Improving Sieve Tray Performance with Knitted Mesh Packing," *Ind. Eng. Chem., Process. Des. Dev., 23*, 561–565 (1984).
2. A. B. S. H. Salem and A. A. Alsaygh, "Better Sieve-Tray Add Packing," *Hydrocarbon Process., 67*(5), 76G–76H (1988).
3. G. X. Chen, A. Afacan, C. Xu, and K. T. Chuang, "Performance of Combined Mesh Packing and Sieve Tray in Distillation," *Can. J. Chem. Eng., 68*, 382–386 (1990).
4. M Dribika and M. W. Biddulph, "Surface Tension Effects on a Large Rectangular Tray with Small Diameter Holes," *Ind. Eng. Chem., Res., 26*, 1489–1494 (1987).
5. J. Prausnitz, T. Anderson, E. Grens, C. Eckert, R. Hseih, and J. O'Connel, *Computer Calculations for Multicomponent Vapor–Liquid and Liquid–Liquid Equilibria*, Prentice-Hall, Englewood Cliffs, New Jersey, 1980, p. 101.
6. J. W. Tierney and N. A. Abdelmalek, "Algorithms for Total Reflux Calculations," *Ind. Eng. Chem., Fundam., 19*, 404–410 (1980).
7. N. J. Anderson and M. F. Doherty, "An Approximate Model For Binary Azeotropic Distillation Design," *Chem. Eng. Sci., 39*, 11–19 (1984).
8. J. Harg, "Equation to Replace Gilliland Correlation," *Hydrocarbon Process., 3*, 48–50 (1985).

Received by editor December 21, 1992