Performance of Tray Columns Operated in the Cycling Mode

J. A. GERSTER and H. M. SCULL

University of Delaware, Newark, Delaware

Tray efficiencies were measured for desorbing ammonia from water by air in a small sieve-tray column operated in the cycling mode, that is, with alternate flow of vapor and liquid. The actual efficiency improvement obtained was compared with that theoretically possible assuming the liquid flows without mixing when dropped. A mixing model was proposed and the mixing parameter evaluated from the experimental data.

Controlled cyclic operation of stage-by-stage countercurrent mass transfer columns, first proposed by Cannon (*1*, *2*) consists of alternately allowing vapor and liquid streams to flow. During the vapor-flow cycle, the liquid remains on the tray and is stripped of the more volatile component. When the vapor is stopped, reflux and feed liquids are supplied, and liquid is dropped from each tray to the tray below.

Cycled operation was shown by McWhirter and Cannon (*6*) and McWhirter and Lloyd (*7*) to offer both efficiency improvement and capacity increase. The capacity increase was apparently because the cycled column was compared with the same column operated as a dual-flow column. If the cycled column were compared with a conventional cross flow column, any capacity increase would be mainly due to the lack of downcomers in the cycled column. The theory of the efficiency improvement of cycled columns has been developed by several authors, notably Sommerfeld et al. (*9*), Robinson and Engel (*8*), and Horn (*3*, *4*). The important parameters involved are the separation factor λ, defined as the ratio of the slopes of the equilibrium curve and operating line, the Murphree point efficiency E, and the amount of liquid dropped per cycle, expressed as a fraction of the tray holdup ϕ. The previous papers have shown that considerable efficiency improvement is possible with high values of point efficiency or separation factor. The improvement is also maximized for integral values of ϕ.

In all of the previous work, it has been assumed that there was no mixing of liquid during the liquid drop cycle (that is, the liquid dropped in plug flow). It is obvious that increased liquid mixing decreases the efficiency improvement of a cycled column. May and Horn (*5*) have developed a solution for the efficiency improvement in a cycled process assuming the stirred-tanks-in-series model for liquid mixing.

SCOPE

The purpose of the present study was to determine the efficiency improvement that could be achieved in practice with standard sieve trays. Furthermore, it was anticipated that plug flow of liquid could not be realized in a real situation, so that a one-parameter mixing model was developed and the mixing coefficient determined experimentally. The form of the model chosen was based upon qualitative observations of the operating column.

EXPERIMENTAL

Desorption of ammonia rich water by air was carried out in a sieve-tray column operated in the cyclic manner at essentially atmospheric pressure. The column was 6 I.D. and contained up to four trays; the tray spacing was 24 in., and the column itself was of glass sections. The tray contained 0.25 in. diameter holes on a 0.5 in. square spacing; the hole area or free area was 13.9% of the column cross section. The ammonia-air-water system was chosen because of the ease of handling and analysis, because of the availability of precise equilibrium data, and because the equilibrium slope was linear and could be varied by varying the temperature of operation.

A schematic of the equipment is shown in Figure 1. Air from a Roots gas pump was fed to the column and cycled by a pair of 2 in. solenoid valves. The solenoids were operated by two electronic cycle timers which allowed independent adjustment of the vapor flow cycle and vapor off (this is, liquid drop) cycle. The air rate was measured by an orifice connected to a differential pressure cell and a pressure recorder. The response of the orifice was found to be rapid enough so that a steady pressure drop could be assumed for the entire vapor flow cycle with negligible error (that is, a perfect pulse of vapor was assumed). The tray temperatures were measured by thermocouples.

Above the top tray and vapor outlet was another sieve tray. A plate covered underneath with soft rubber and attached to a solenoid was placed on this tray. The feed solution was fed continuously to this tray. When the solenoid lifted the plate, the liquid then streamed through the tray holes as if from another tray. When the plate was lowered, the liquid did not flow. This method eliminated the end effect caused by continuous liquid feed and to some extent justified the use of a small number of trays.

The outlet liquid sample was collected by a rectangular funnel below the bottom tray and above the vapor inlet. It collected about 20% of the total liquid from the bottom tray. This was necessary to remedy a wetted wall effect in the bottom of the column. This effect was abetted by the vapor entering perpendicular to the column. Both the sample and drain liquid were discharged continuously.

EXPERIMENTAL PROCEDURE AND PROBLEMS

The column was initially run with air-water until the tray

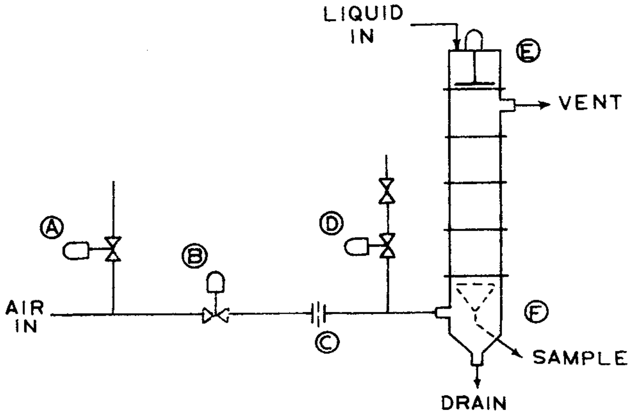

Fig. 1. Diagram of apparatus.

H. M. Scull is with the Ethyl Corporation, Baton Rouge, Louisiana.

holdups were steady, at which time the feed was switched to the ammonia solution. From computer solutions conservative estimates of the time to attain cyclic steady state were obtained. (These estimates were also checked experimentally.) After this time had elapsed, samples were collected. To terminate the run the air was shut off and the total column holdup collected from the bottom. Knowing the liquid flow rate and the total cycle time, we could then calculate ϕ by assuming equal holdup on each tray.

Under the operating conditions, the entrainment from the top tray averaged from 2 to 3% of the total inlet liquid flow. Since visually the tray-to-tray entrainment appeared negligible, it was assumed that most of the entrainment occurred when the vapor flow started and was caused by dropping liquid being flown out the outlet vent.

Under some conditions, the liquid and froth on a tray would slosh back and forth in a steady periodic manner causing excessive weepage. To remedy this, thin eggcrate type of baffles, 1.5 in. high, were installed on each tray.

The bottom two trays in the four-tray column were found to operate with a much greater holdup (that is, froth height) than the top ones. This is not unusual when one considers that the liquid leaving the bottom tray is displacing vapor in bottom of the column. The resultant pressure increase slowed the flow of liquid which in turn caused an increase in the holdup, particularly on the bottom trays. This was remedied by placing a solenoid operated vent line in the bottom of the column (see Figure 1). A valve was placed on this line to control the amount of venting. With air-water runs, the valve was opened a little at a time until it no longer affected the tray holdups. At this valve setting all subsequent ammonia runs were made.

POINT EFFICIENCY

In order to determine quantitatively the efficiency improvement of cycled operation, tray-point efficiencies were measured. Writing an unsteady state material balance on a single tray with vapor flow but no liquid flow, we get

$$E = \frac{H_{lm}}{KVt} \ln \frac{x(0)}{x(t)} \qquad (1)$$

The assumptions for the above equation are:

1. Henry's law equilibrium.
2. Time independent point efficiency.
3. Small, constant weepage rate.

The term H_{lm} in Equation (1) is the log mean of the initial and final holdups, and the calculated efficiency corresponds to this holdup.

A point efficiency run was started with air blowing through a dry tray open to the atmosphere. At time zero, a weak ammonia solution of known concentration was quickly dumped manually onto the tray from a portable tank containing a trap door. Runs were made of either 20, 40, or 60 sec. duration. At the end of a run, the vapor was shut off and the total liquid collected and analyzed. Since at the beginning of a run the liquid could not be dumped onto the tray instantaneously, the sample at 20 sec. was considered the starting point for calculation purposes. Thus, the effective run times were 20 and 40 sec. This method is valid if the method of dumping the liquid initially is consistent from run to run. The results of the point efficiency runs are shown in Figure 2. The vapor rate corresponded to the rate during cycled operation.

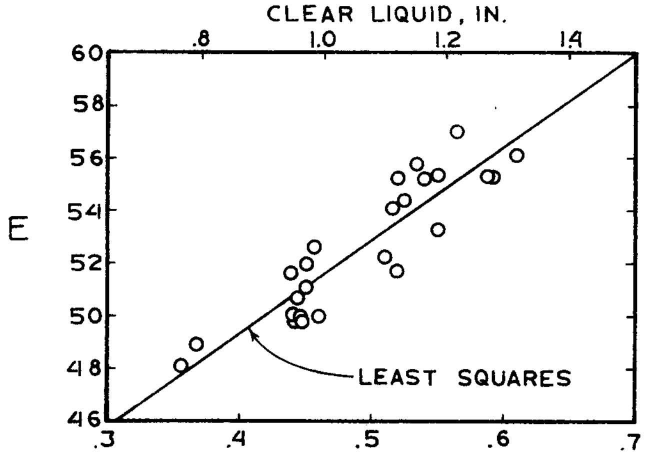

Fig. 2. Point efficienies for ammonia-air-water.

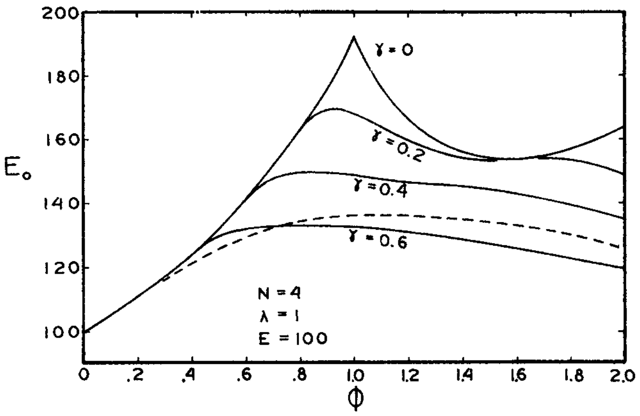

Fig. 3. Computer solutions for efficiency improvement due to cycling.

THEORY

The equations describing the vapor flow cycle are

$$H \frac{dx_n}{dt} = V\,(y_{n-1} - y_n) \qquad (2)$$

$$E = \frac{y_n - y_{n-1}}{Kx_n - y_{n-1}} \qquad (3)$$

By defining

$$\overline{V} = V\,\frac{\tau_V}{\tau_C}$$

$$\phi = \frac{\overline{L}\,\tau_C}{H}$$

$$\theta = \frac{t}{\tau_V}$$

Equation (2) then becomes

$$\frac{dx_n}{d\theta} = \phi \frac{\overline{L}}{\overline{V}}\,(y_{n-1} - y_n) \qquad (4)$$

The initial or periodicity condition for this equation is determined by the assumptions made about the liquid mixing during the liquid drop cycle. For the case of no mixing, the periodicity condition is

$$x_n(0) = \phi x_{n+1}(1) + (1 - \phi)\,x_n(1) \qquad (5)$$

for

$$0 \leq \phi \leq 1$$

This equation can be modified for values of ϕ greater than unity.

In practice, it was observed that some of the liquid must drop without mixing, since it obviously cannot mix with the liquid on the tray below while it is falling between trays. However, once this liquid strikes the liquid on the tray below, some degree of mixing must occur. For small values of ϕ, one would expect the assumption of no mixing

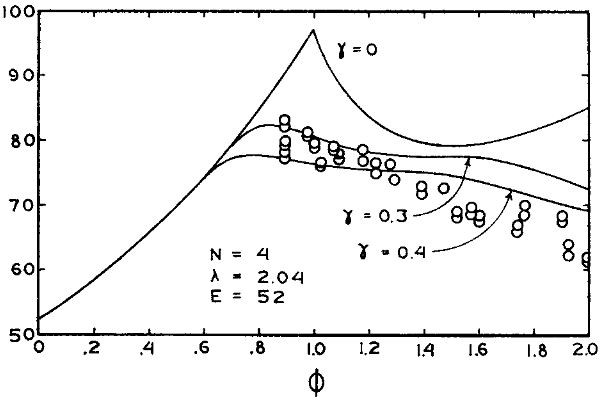

Fig. 4. Experimental cycled efficiencies, four-tray column, low λ.

to be valid, since none of the dropping liquid would reach the tray below until after the vapor flow began. These observations were expressed in a model of the liquid mixing, which consisted of a plug flow section in series with an ideally mixed stirred tank. The mixing coefficient, γ is the fraction of the total tray holdup which is considered to be ideally mixed. This coefficient might be termed the *fraction mixed.*

Let z_n be the composition of the liquid in the stirred tank of tray n. The material balance during liquid flow gives

$$\gamma H \frac{dz_n}{dt} = \frac{\phi H}{\tau_L} [u(t - \tau_D)\, z_{n+1}(t - \tau_D) - z_n] + \frac{\phi H}{\tau_L} [1 - u(t - \tau_D)]\, x_n(1) \tag{6}$$

where τ_D, the transport delay time, is defined by

$$\tau_D = \frac{1 - \gamma}{\phi} \tau_L \tag{7}$$

and $u(t - \tau_D)$ is the transport delay function defined by

$$u(t - \tau_D) = \begin{cases} 0 & t < \tau_D \\ 1 & t \geqq \tau_D \end{cases} \tag{8}$$

Now, define

$$\theta = \frac{t}{\tau_L}; \qquad \theta_D = \frac{1 - \gamma}{\phi}$$

Thus, Equation (6) becomes

$$\frac{dz_n}{d\theta} = \frac{\phi}{\gamma} [u(\theta - \theta_D)\, z_{n+1}(\theta - \theta_D) - z_n] + \frac{\phi}{\gamma} [1 - u(\theta - \theta_D)]\, x_n(1) \tag{9}$$

with the initial condition

$$z_n(0) = x_n(1) \tag{10}$$

The periodicity condition for Equation (4) is thus

$$x_n(0) = \gamma z_n(1) + \phi \int_0^1 z_{n+1}\, d\theta + (1 - \gamma - \phi)\, x_n(1) \tag{11}$$

for

$$1 \leqq \theta_D$$

and

$$x_n(0) = \gamma z_n(1) + \phi \int_{1-\theta_D}^1 z_{n+1}\, d\theta \tag{12}$$

for

$$1 > \theta_D$$

Examination of the right-hand side of (9) indicates that for $1 \leqq \theta_D$

$$z_n(\theta) = x_n(1)$$

Thus, (11) becomes

$$x_n(0) = \phi\, x_{n+1}(1) + (1 - \phi)\, x_n(1)$$

which is identical to Equation (5) for no mixing. This confirms that for a given value of γ there is a value of ϕ below which the liquid from a tray does not reach the next tray before the liquid flow cycle ends, and no mixing applies.

These equations were solved numerically on a SDS-9300 computer. Figure 3 shows the overall efficiency $N_I/N \times 100$ plotted vs. ϕ for various values of γ in a four-tray column. The dashed line corresponds to Horn's analysis of mixing with four stirred tanks in series. The difference between the models is small, being primarily that Horn's analysis predicts maximum efficiency improvement at values of ϕ greater than unity, while the model presented here predicts the maximum at ϕ less than unity.

However, the model of this study has the advantage that it gives greater insight into methods for minimizing mixing. For example, increasing the hole size to cause the liquid to drop more rapidly should decrease the fraction mixed, γ. Also, decreasing the holdup for a given amount of liquid dropped should decrease γ. Unfortunately, both of these steps would cause smaller point efficiencies. The tray spacing would obviously have an effect on γ also.

RESULTS AND DISCUSSION

The scope of the runs reported in this paper consists of a variation in ϕ, the fraction of the liquid tray holdup dropped each cycle, and a variation in λ, the separation factor. The gas and liquid rates were not varied, since their magnitudes affect primarily the magnitudes of the vapor flow cycle and the liquid drop cycle. The $\overline{L}/\overline{V}$ ratio for all runs was approximately 0.6. Because the point efficiencies were relatively low, λ was given a large enough value that an appreciable efficiency improvement could be attained. The value of λ was varied by varying the temperature of the run. The gas rate was chosen at a rate high enough to be consistent with commercial operation and to minimize weepage. The gas rate expressed as an F factor, where F is the product of the gas rate in cubic feet per second per square feet of tower cross section, and the square root of the vapor density in pounds per cubic feet was chosen as 2.0.

Figures 4 and 5 show the overall efficiency (defined as $N_I/N \times 100$) for a four-tray column at two values of λ. The individual values of λ and E for each data point did not vary from the average values by more than 1%.

Inspection of the figures shows that the slope of the data points is slightly greater than the slope of the model for any particular value of γ. In this respect, the model could be improved by relaxing the assumption that the stirred tank section is perfectly mixed or by making γ a function of ϕ. However, this would add another mixing

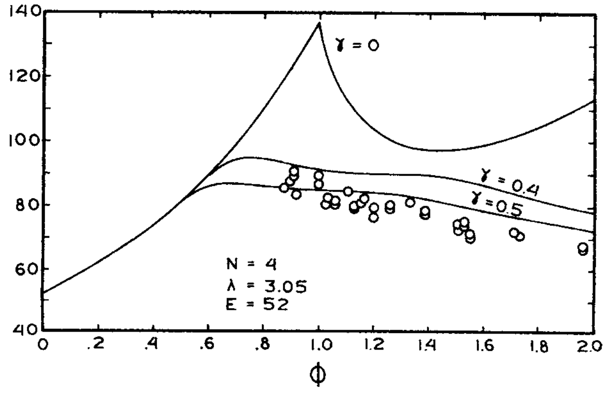

Fig. 5. Experimental cycled efficiencies, four-tray column, high λ.

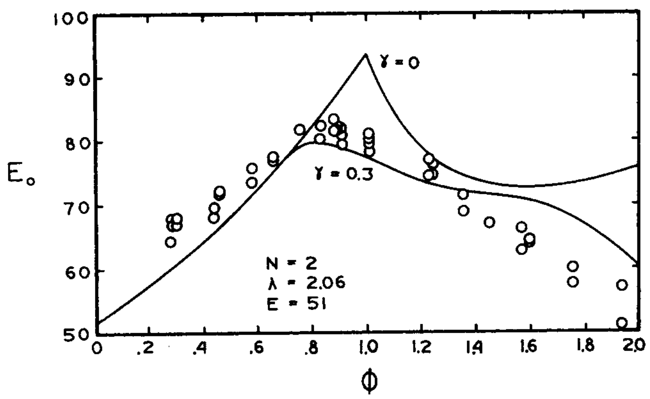

Fig. 6. Experimental cycled efficiencies, two-tray column, low λ.

parameter and was not considered justified.

Figures 4 and 5 show that the data do match the theory fairly well, and that the value of γ for this particular apparatus lies in the range 0.35 to 0.55.

One reason for performing experiments at two different liquid temperatures, 84° and 100°F., was to obtain data at two different values of λ; a variation in λ causes a variation in degree of efficiency improvement. However, the small change in liquid temperature should not cause any appreciable change in the liquid mixing mechanism, from which it follows that the values of γ obtained on Figures 4 and 5 should be identical. The fact that the γ values are slightly greater on Figure 5, where λ is higher, cannot be explained from any theoretical or experimental basis, and the difference must then be attributed to the precision in measurement of γ which must be no better than $\pm$ 0.10.

The vapor flow and liquid drop cycles for Figures 4 and 5 ranged from 24 and 0.6 sec., respectively, for the low values of ϕ to 51 and 1.25 sec. for the high values of ϕ.

Attempts were made to run at lower values of ϕ, but hydraulic effects prevented this. At the low values of ϕ, the second tray had a very high holdup, while the bottom tray had very little. The top two trays were largely unaffected. This effect was believed to be somehow related to the very short liquid drop cycles required. The holdup on the bottom trays could be made more nearly equal by closing the bottom vent, but then both holdups were much higher than on the top two trays.

It was found that low values of ϕ could be obtained from a two-tray cycled column by manipulating the bottom vent. Figure 6 shows efficiency data for a two-tray column. The form of the data appears to support the model for values of ϕ less than unity; for larger values the data drop off faster than the model, as previously noted. The fact that the experimental efficiencies are slightly higher than the model in the low ϕ range could possibly be due to a slight end effect not entirely corrected by the method of introducing the liquid to the top of the column. The vapor flow and liquid drop cycles for the lower values of ϕ were about 7.5 and 0.4 sec., respectively. The magnitude of γ in this case is similar to the values determined earlier for the four-tray column. However, the values from Figure 6 for the two-tray column are probably less precise because of the greater importance of end effects.

CONCLUSIONS

In summary, the experimental efficiencies agreed fairly well with the proposed model. Also, considerable efficiency improvement for the cycled column over a conventional column was demonstrated; the magnitude of this improvement would have been even greater if the point efficiency had been larger. However, the tray design for the present experiments, a sieve tray with large holes and small liquid holdup, was chosen so as to minimize mixing of liquid when dropped rather than to promote high point efficiency.

More experiments are currently underway in these laboratories to optimize tray designs for use in cycled columns and to overcome the need for venting of the trays during the liquid drop cycle. A 2 ft. tower is being employed in these later studies. Obviously, such additional tests are needed before commercial designs can be made. However, the values of γ obtained from the tests reported in this paper give some indication of the degree of the actual efficiency improvement which can be expected from cycled columns.

ACKNOWLEDGMENT

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NOTATION

E = Murphree point efficiency
H = tray holdup
K = Henry's law coefficient = y/x
$\overline{L}$ = average liquid flow rate for entire cycle
N = number of cycled trays
N_I = number of ideal, (E = 100) conventional trays necessary to effect the same separation as N cycled trays
t = time
V = instantaneous vapor flow rate
$\overline{V}$ = average vapor flow rate for entire cycle
u = transport delay function
x_n = mole fraction of reference component in liquid on tray n
y_n = mole fraction of reference component in vapor leaving tray n
z_n = mole fraction of reference component in stirred tank of tray n

Greek Letters

γ = fraction of a tray that is perfectly mixed during liquid flow cycle
λ = separation factor
θ = dimensionless time
θ_D = dimensionless transport delay time
τ_D = transport delay time
τ_C = time for total cycle
τ_V = time for vapor flow cycle
τ_L = time for liquid flow cycle
ϕ = liquid dropped per cycle expressed in units of tray holdup

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