# Effect of Vapor Rate and Weir Height on Foaming

GERALD P. KUEHLER and MATTHEW VAN WINKLE
The University of Texas, Austin, Tex. 78712

**A quantitative study has been made of the effects of vapor rate and weir height on the froth height, froth density, plate pressure drop, and plate efficiency using the binary system methyl ethyl ketone–toluene in a 6-inch laboratory column. The froth density was determined by photographing the glass-enclosed test tray at random intervals and carrying out a statistical analysis of the data. The results indicate that the measurements were precise. The weir height was found to be the most important correlating variable. Froth height increased gradually with increasing vapor rates, but neither equivalent liquid head nor efficiency was related to vapor rate. Both could, however, be correlated with weir height.**

IN OPERATION of sieve-tray equipment, a suspended layer of liquid in a gas in the form of a foam or froth is produced. While the froth represents a highly turbulent gas-liquid system which results in an extensive phase contact area and presents a low diffusion resistance, the foam can best be described by a large group of cellular, relatively stable bubbles of close proximity (*1, 6*). This is visually very different from the clouds of bubbles in rapid motion which are characteristic of froths. Frothing was the principal phenomenon encountered in this series of tests.

The existence of a froth or foam on the tray of a distillation column has significant influences upon the operation of the column, and froth or foam height has been shown to be an important correlating parameter in predicting efficiency and pressure drop (*2, 3, 5–8*). It is especially important in determining the space available for disengagement of entrained liquid droplets. Severe foaming decreases this disengaging space between the trays, resulting in decreased efficiency and increased pressure drop. Because of the lack of data concerning the hydrodynamic behavior of sieve plates operating under distilling conditions, this investigation was undertaken. Its objective was to determine the significance of vapor rate and weir height and the general trends in their effects on column behavior. It was hoped that this series of tests would indicate patterns of behavior which could then be studied in more detail.

## EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental work was carried out in a 6-inch Double-Tough borosilicate glass pipe laboratory-constructed distillation column containing three sieve trays, a central test tray, and two distribution trays. The tray hole diameter was 0.1563 inch, and the ratio of hole area to active area was 0.097.

The distillation column flow scheme is illustrated in Figure 1 and the test tray details are summarized in Table I. The binary, methyl ethyl ketone–toluene, was the test system and the distillations were conducted at atmospheric pressure. The relative volatility ranged from about 3.0 to 3.4 over the temperature and composition range.

The experimental procedure involved taking a series of photographs together with samples of the test tray liquid and vapor at a given weir height and vapor rate, then adjusting operation to a different vapor rate by changing the heat supplied to the reboiler. In each case the column was allowed to operate at steady-state conditions for a minimum of 1 hour before taking any data. All runs represented conditions of total reflux. The photographic technique for determining the foam height was that used by Redwine *et al.* (*8*).

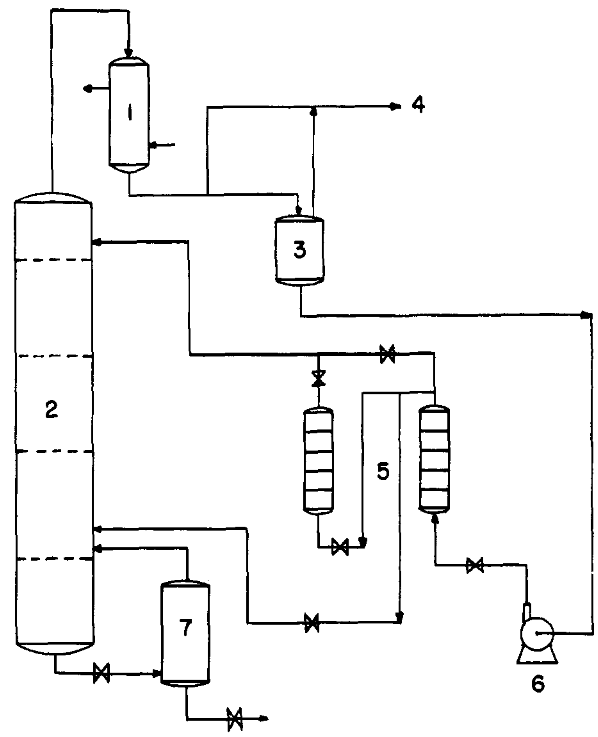


Figure 1. Schematic of test column

1. Overhead condenser. 2. Test column. 3. Reflux accumulator. 4. Vapor vent line. 5. Liquid rotameters. 6. Reflux pump. 7. Reboiler

Table I. Test Tray Specifications

(Single-tray, single-pass)

| | |
|---|---|
| Column internal diameter, inches | 5.881 |
| Cross sectional area, sq. ft. | 0.1882 |
| Active (bubbling) area, sq. ft. | 0.1503 |
| Downcomer type | Segmental, vertical |
| Downcomer area, sq. ft. | 0.0190 |
| Downcomer area, % cross-sectional area | 10.1 |
| Perforation diameter, inch | 0.1563 |
| Pitch/diameter, equilateral triangular centers | 2.80 |
| Number of perforations | 109.00 |
| Total perforation area, sq. ft. | 0.0145 |
| Test section tray spacing, inches | 18.00 |
| Weir type | Straight |
| Weir length, inches | 4.250 |
| Tray thickness, inch | 0.125 |
| Downcomer clearance, inch | 0.500 |
| (No seal pans or inlet weirs were used) | |

## EXPERIMENTAL RESULTS

The experimental data and correlation parameters are listed in Tables II and III. The froth height, $\bar{h}_F$, equivalent clear liquid head, $\bar{h}_L$, and foam density, $\bar{\phi}$, are average values determined from a set of at least ten photographs for each data point. Mathematical analysis of the data indicated that the measurements were precise, yielding maximum 90% confidence limits for the foam height, equivalent clear liquid head, and froth density of $\pm 0.24$ inch, $\pm 0.11$ inch, and $\pm 0.02$, respectively. The vapor rates under investigation ranged from 0.80 to 2.45 feet per second ($F_{AA}$ = 0.80 to 1.12) and the weir heights studied were ¾, 1½, 3, 4½, and 6 inches.

**Effect of Vapor Rate on Froth Density, $\phi$.** From the results of the photographic data the froth density, $\phi$, was calculated as the ratio of the equivalent clear liquid head, $\bar{h}_L$, to the froth height, $h_F$. The factor $F_{AA}$, vapor flow parameter, and weir height, $h_w$, were used as correlating parameters. While the froth height was found to be linearly related to the flow parameter (Figure 2) at each weir height studied, the equivalent clear liquid did not depend upon the flow parameter at a given weir height. The relationship between equivalent clear liquid head and weir height for all vapor and liquid rates is shown in Figure 3. The effect of weir height on froth density is shown in Figure 4 for the 3-, 4½-, and 6-inch weir heights. The data for the ¾-, 1½-, and 3-inch weir heights fell essentially on the same line. Because of its importance in predicting pressure drop, the aeration factor, $\beta$, is also plotted in Figure 4. This factor is related to the froth density by the following semi-theoretical equation, derived by Hutchinson *et al.* (4):

$$\beta = \frac{\bar{\phi} + 1}{2} \qquad (1)$$

Table II. Experimental Efficiency Results

| $h_w$ | Mole % $x_{tray}$ | Mole % $y_{tray}$ | $\alpha$ | Efficiency, % |
|---|---|---|---|---|
| ¾ | 16.8 | 30.0 | 3.04 | 71.6 |
| | 16.0 | 29.0 | 3.21 | 69.5 |
| | 8.5 | 17.3 | 3.25 | 68.7 |
| | 0.1 | 1.5 | ... | ... |
| | 1.9 | 3.0 | ... | ... |
| | 12.0 | 22.8 | 3.20 | 70.6 |
| 1½ | 24.2 | 40.0 | 2.75 | 73.4 |
| | 17.0 | 31.0 | 2.96 | 72.5 |
| | 15.7 | 29.5 | 3.03 | 72.5 |
| | 11.5 | 22.9 | 3.14 | 72.0 |
| | 9.2 | 19.5 | 3.27 | 73.5 |
| | 6.8 | 15.0 | 3.18 | 76.0 |
| 3 | 6.5 | 15.8 | 3.18 | 87.5 |
| | 5.9 | 14.7 | 3.11 | 90.9 |
| | 6.0 | 16.0 | 3.20 | 93.2 |
| | 5.0 | 13.7 | 3.35 | 91.5 |
| | 4.3 | 11.8 | 3.23 | 92.1 |
| | 5.1 | 13.9 | 3.28 | 92.8 |
| 4½ | 10.0 | 23.3 | 3.23 | 85.9 |
| | 8.5 | 20.2 | 3.28 | 84.3 |
| | 8.8 | 21.0 | 3.26 | 86.4 |
| | 6.3 | 15.4 | 3.17 | 86.2 |
| | 3.8 | 10.3 | 3.34 | 88.8 |
| | 7.0 | 17.2 | 3.26 | 86.3 |
| | 5.9 | 14.6 | 3.19 | 86.8 |
| 6 | 10.6 | 24.5 | 3.41 | 80.9 |
| | 10.1 | 22.2 | 3.25 | 78.9 |
| | 11.0 | 25.5 | 3.23 | 81.0 |
| | 8.4 | 20.0 | 3.28 | 83.3 |
| | 9.5 | 22.5 | 3.24 | 78.4 |
| | 8.8 | 21.0 | 3.37 | 83.5 |

Table III. Experimental Results and Correlation Parameters

| $h_w$, Weir Height, Inches | $V$, Vapor Rate, Lb./Hr. | $F_{AA}$, Flow Par. | Froude No. | $h_t$, Tray $\Delta P$, Inches $H_2O$ | $\bar{h}_F$, Av. Froth Ht., Inches | $\bar{h}_L$, Av. Liquid Ht., Inches | $\bar{\phi}$, Av. Froth Density | $\beta$, Aer. Fact. | $E$, Eff., % |
|---|---|---|---|---|---|---|---|---|---|
| ¾ | 141.1 | 0.571 | 1.84 | ... | 1.447 | 0.315 | 0.217 | 0.609 | 71.6 |
| | 205.9 | 0.833 | 3.06 | ... | 1.571 | 0.404 | 0.257 | 0.629 | 69.5 |
| | 151.3 | 0.609 | 1.65 | 0.510 | 1.265 | 0.396 | 0.313 | 0.656 | 68.7 |
| | 137.3 | 0.548 | 1.36 | 0.460 | 1.127 | 0.385 | 0.341 | 0.671 | ... |
| | 178.8 | 0.714 | 3.16 | 0.520 | 1.376 | 0.281 | 0.204 | 0.602 | ... |
| | 209.9 | 0.845 | 2.39 | 0.605 | 1.566 | 0.527 | 0.336 | 0.668 | 70.6 |
| 1½ | 89.8 | 0.364 | 0.39 | 0.605 | 1.701 | 0.615 | 0.361 | 0.681 | 73.4 |
| | 114.8 | 0.464 | 0.62 | 0.685 | 1.934 | 0.625 | 0.323 | 0.662 | 72.5 |
| | 181.7 | 0.736 | 1.65 | 0.755 | 2.211 | 0.588 | 0.266 | 0.633 | 72.5 |
| | 215.4 | 0.869 | 2.86 | 0.820 | 2.286 | 0.469 | 0.205 | 0.603 | 72.0 |
| | 145.3 | 0.586 | 0.92 | 0.770 | 2.080 | 0.661 | 0.318 | 0.659 | 73.5 |
| | 161.7 | 0.651 | 1.17 | 0.805 | 2.090 | 0.642 | 0.307 | 0.654 | 76.0 |
| | 124.1 | 0.499 | 0.43 | 0.910 | 2.551 | 1.025 | 0.401 | 0.701 | 87.5 |
| | 142.8 | 0.574 | 0.63 | 0.935 | 3.199 | 0.922 | 0.288 | 0.644 | 90.9 |
| | 164.6 | 0.662 | 0.84 | 1.090 | 3.760 | 0.924 | 0.246 | 0.623 | 93.2 |
| | 184.3 | 0.741 | 1.09 | 1.185 | 3.648 | 0.892 | 0.245 | 0.622 | 91.5 |
| | 206.3 | 0.830 | 1.45 | 1.175 | 3.876 | 0.842 | 0.217 | 0.609 | 92.1 |
| | 262.9 | 1.060 | 2.67 | 1.400 | 4.044 | 0.749 | 0.185 | 0.593 | 92.8 |
| 4½ | 212.4 | 0.857 | 1.09 | 1.480 | 5.004 | 1.194 | 0.239 | 0.619 | 85.9 |
| | 193.8 | 0.783 | 0.97 | 1.390 | 4.515 | 1.135 | 0.251 | 0.626 | 84.3 |
| | 174.7 | 0.706 | 0.85 | 1.300 | 4.306 | 1.054 | 0.245 | 0.622 | 86.4 |
| | 162.8 | 0.655 | 0.72 | 1.255 | 3.952 | 1.051 | 0.266 | 0.633 | 86.2 |
| | 142.4 | 0.573 | 0.62 | 1.100 | 3.284 | 0.937 | 0.285 | 0.643 | 88.8 |
| | 266.4 | 1.074 | 2.06 | 1.830 | 5.772 | 0.993 | 0.172 | 0.586 | 86.3 |
| | 233.6 | 0.942 | 1.61 | 1.745 | 5.237 | 0.978 | 0.187 | 0.593 | 86.8 |
| 6 | 209.3 | 0.844 | 1.27 | 1.165 | 4.995 | 1.180 | 0.236 | 0.618 | 80.9 |
| | 190.5 | 0.768 | 1.13 | 1.100 | 3.313 | 0.931 | 0.281 | 0.641 | 78.9 |
| | 229.3 | 0.927 | 1.17 | 1.235 | 5.231 | 1.312 | 0.251 | 0.625 | 81.0 |
| | 240.1 | 0.968 | 1.20 | 1.245 | 5.741 | 1.384 | 0.241 | 0.621 | 83.3 |
| | 157.4 | 0.634 | 0.78 | 1.020 | 3.107 | 0.920 | 0.296 | 0.648 | 78.4 |
| | 276.8 | 1.119 | 1.56 | 1.400 | 6.690 | 1.434 | 0.214 | 0.607 | 83.5 |

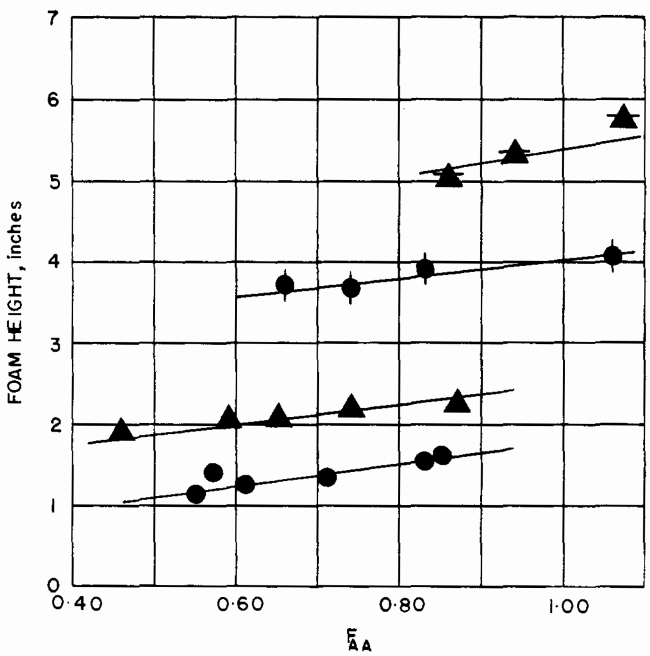


Figure 2. Relation of foam height to flow parameter

$h_w$, Inches

● 0.75
▲ 1.50
● 3.00
▲ 4.50
● 6.00

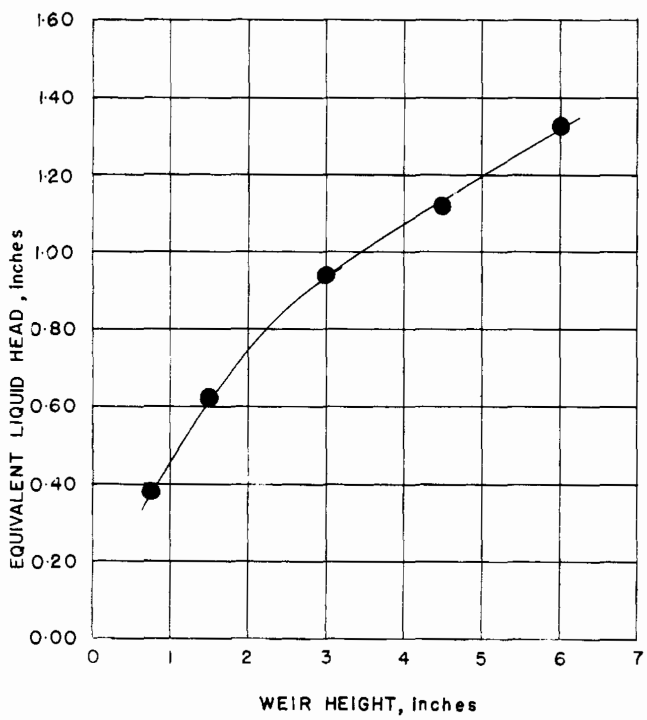


Figure 3. Relation of equivalent liquid head to weir height

**Over-all Efficiency, *E*.** The theoretical number of plates, $n_T$, was calculated using Underwood's equation (*10*) for columns operating at total reflux:

$$n_T = \frac{\log \dfrac{y(1-x)}{x(1-y)}}{\log \alpha} \tag{2}$$

where the relative volatility $\alpha$, for the binary mixture was calculated from the equilibrium data (*9*) as follows:

$$\alpha = \frac{y^*(1-x)}{x(1-y^*)} \tag{3}$$

Figure 5 indicates that over the range of vapor rates studied in this experimental column, the efficiency is not affected by vapor rate, but only by weir height. In a similar column Redwine and Van Winkle (*8*) also observed that efficiency was not affected by vapor rate for the methyl ethyl ketone–toluene binary system at a weir height of ¾ inch. The efficiency–weir height relationship indicates an efficiency maximum of 92% at a 3-inch weir height. This can be explained by the concepts of liquid entrainment, interfacial area, vapor-liquid contact time, and mass transfer. At low weir heights the foam height is low, causing small interfacial areas which result in short vapor-liquid contact times and, hence, poor mass transfer. There is, however, no entrainment. Although the interfacial area, time of vapor liquid contact, and mass transfer continue to increase at weir heights in excess of 3 inches, there is a gradual decline in efficiency as a result of entrainment at the 18-inch tray spacing studied. For greater tray spacing the entrainment effect on efficiency should be less, resulting in higher efficiencies at the higher weir heights.

**Effect of Froth Height on Plate Pressure Drop, $h_t$.** Figure 6 shows the linear increase in plate pressure drop with froth height and indicates the importance of froth height in correlating pressure drop. An important observation from

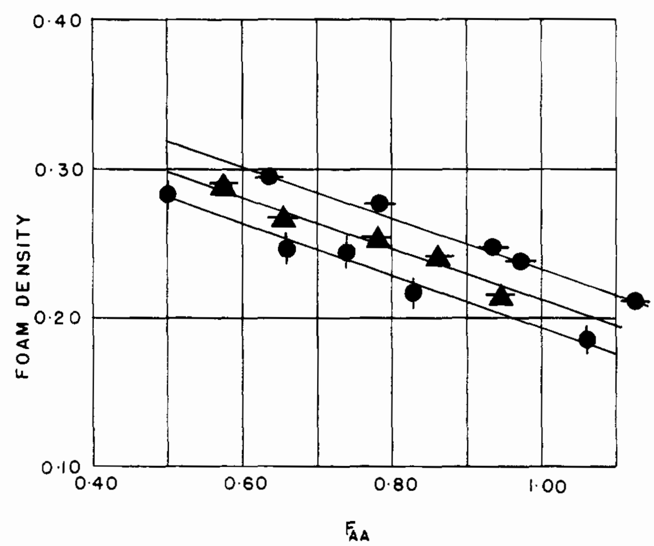


Figure 4. Relation of foam density to flow parameter

$h_w$, Inches

● 3.0
▲ 4.5
● 6.0

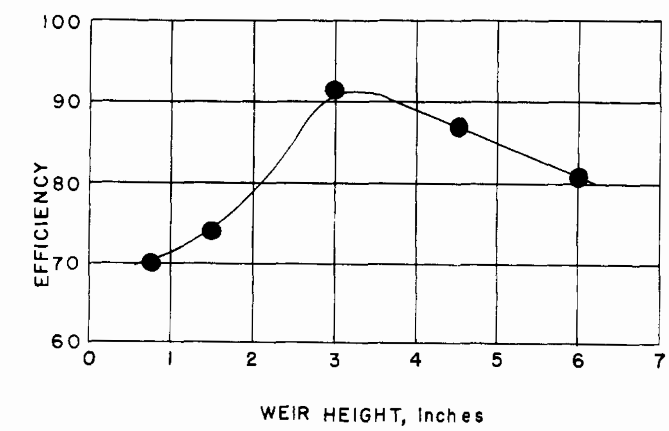


Figure 5. Relation of efficiency to weir height

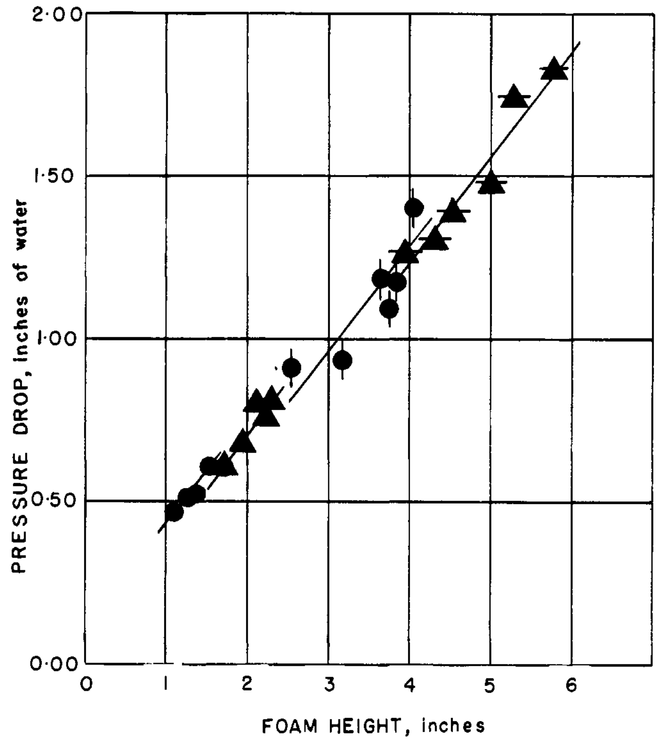


Figure 6. Relation of pressure drop to foam height

$h_w$, Inches

0.75 4.50
1.50 6.00
3.00

Figure 6 should be noted; every increase in weir height shifts the curve downward. This seems logical, since it has been shown that the equivalent clear liquid head does not increase linearly with weir height, but falls off gradually, and that at any given weir height the equivalent clear liquid head is constant with vapor rate.

## ACKNOWLEDGMENT

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## NOMENCLATURE

- $AA$ = cross-sectional area of plate minus 2 (downcomer area)
- $E$ = over-all column efficiency (test plate), $100/n_T$
- $F_{AA}$ = vapor flow parameter, = $U_{AA}\rho_V^{1/2}$
- $g$ = gravity acceleration, 32.17 ft./sec.$^2$
- $\overline{h}_F$ = average froth height, inch
- $\overline{h}_L$ = average equivalent clear liquid head, inch
- $h_t$ = total wet tray pressure drop, inches of water
- $h_w$ = weir height, inches
- $n_T$ = theoretical number of plates required for a separation, Equation 2
- $U_{AA}$ = vapor velocity in tower active area, feet/sec.
- $V$ = vapor rate, lb./hr.
- $x$ = liquid mole per cent MEK on test tray
- $y$ = vapor mole per cent MEK above test tray
- $y^*$ = vapor composition in equilibrium with liquid of mole per cent $x$

### Greek Symbols

- $\beta$ = average aeration factor, Equation 1
- $\rho_v$ = vapor density, lb./cu. foot
- $\phi$ = average relative froth density, $\overline{h}_F/\overline{h}_L$
- $\alpha$ = relative volatility

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