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Pulsations in Sieve-tray and Bubble-cap Distillation Towers

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A periodic pulsation of the frothing mass of liquid and vapor on a sieve tray and a bubble-cap tray is reported. An equation is proposed which relates the frequency of the oscillation to the velocity of sound, the physical dimensions of the systems, and the flow rates of the gas and liquid. The equation is a modification of the acoustical analogy to the classical Helmholtz resonance in electrical circuits having both capacitance and inductance. The oscillation is shown to decrease back-mixing on the tray, and thus to result in an increase in the Murphree vapor efficiency.

Under certain velocities of flow of liquid and vapor in a bubble-cap and sieve tray, it was noticed that the froth and liquid mass on the tray would oscillate in a direction perpendicular to the flow of the liquid; that is, if the net liquid flow was from right to left, the oscillation would be established from front to back. The particular bubble-cap and sieve trays in question are shown diagrammatically in Figures 1 and 2. The vapor velocity at which the pulsations began was well defined, and further increase in it only increased the amplitude of the wave. The frequency of the oscillations was regular and reproducible and was noted to be a function of the vapor and liquid flow rates. The pulsation was found to occur in every binary-system run in the bubble-cap distillation tower, including several organic-organic and water-organic binary systems as well as steam-water. In the sieve tray only air-water was run, but the oscillation would be expected to occur for any vapor-liquid combination.

The oscillation was shown by Plank (*6*) to increase the number of well-mixed pools (*3*) existing on the tray. A well-mixed plate (unit well-mixed pools) implies back-mixing from the liquid-outlet to the liquid-inlet sides of the tray. Since the oscillations are perpendicular to such a path, the pulsations tend to decrease back-mixing and thus result in a closer approach to an unmixed plate. Such conditions increase the over-all plate efficiency.

For the bubble-cap tray, Figure 3 shows the number of well-mixed pools for several binary distillation systems under both pulsating and nonpulsating operating conditions. The number of well-mixed pools n was calculated from the expression from reference (*3*) relating the Murphree vapor efficiency E_{mv} to the point efficiency E_{OG} under conditions of partial mixing.

$$E_{mv} = B\left[\left(1 + \frac{E_{OG}}{nB}\right)^n - 1\right] \qquad (1)$$

The bubble-cap tray was constructed in such a manner that liquid samples could be obtained from any point along the length of liquid travel. Point efficiencies were calculated from the equation

$$E_{OG} = \frac{(y_n - y_{n-1})}{\left[\int_0^b y_{nb}^* \frac{db}{b} - y_{n-1}\right]} \qquad (2)$$

with liquid samples obtained by traverse along the tray floor in the direction of liquid travel. Such an efficiency has been successfully used by Anderson (*1*), Plank (*6*), and Winslow (*8*). Vapor efficiencies were measured and calculated in the normal way.

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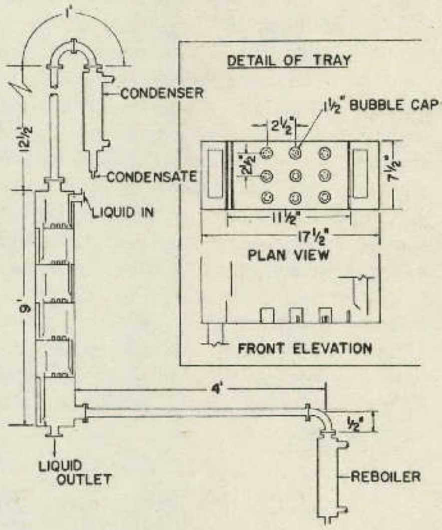


Fig. 1. Bubble-cap distillation tower.

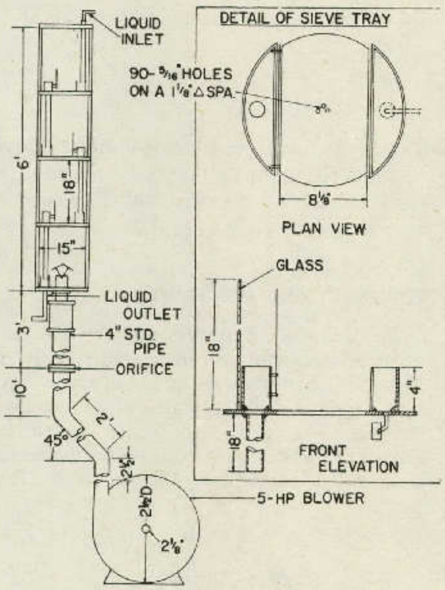


Fig. 2. Sieve-tray tower.

The abscissa of Figure 3, $t_L\sqrt{F_V}$, has been used by Plank (*6*) and Winslow (*8*) to correlate liquid mixing on the particular bubble-cap tray used in this investigation. The term t_L is called the *liquid contact time* and is calculated as

$$t_L = \frac{Z_c A}{L'} \qquad (3)$$

For the data of Figure 3, pulsation occurred in conjunction with the high F_V factor ($F_V = 1.3$) and is represented by the upper line. At the lower F_V factors pulsations did not occur, and these data are shown by the lower dashed line. Assumption of 1.1 well-mixed pools, when in fact $n = 1.6$ well-mixed pools, may result in errors greater than 100% in estimating Murphree vapor efficiencies from point efficiency by the methods described in (*3*).

Operation of a tower in the pulsating region, however, presents certain hydraulic problems. The sloshing of the liquid from front to back can become so violent that liquid from one tray can be thrown up into the tray above long before normal flooding is to be expected. Figure 4 shows successive frames of a motion picture taken of the bubble-cap tower and sieve tray when they are being operated in the pulsating range. The fact that liquid can be thrown up under the tray above is shown more clearly in the pictures of the bubble-cap–tray operation. The average froth height for these conditions is only about one half, or less, of the tray spacing.

Since the behavior was distinctly periodic, it was suspected that an acoustic phenomenon could account for the periodicity. Heath and Elliott (*4*) were able to predict by a simple equation the pulsation frequency in several duct systems used in their study. These had a centrifugal compressor which caused air to flow in the ducts. In a sense, a bubble-cap or sieve-tray distillation tower may be considered to be a duct system. The distillation towers are complicated by the existence of both the liquid and the gas phase, but still they are dynamic, fluid systems. The formula used to predict the frequency of pulsation in the duct systems (*4*) is

$$f = \frac{c}{2\pi}\sqrt{\frac{S'}{lV}} \qquad (4)$$

Richardson (*7*) developed Equation (4) by considering the acoustical analogy of a classical Helmholtz resonator. In an electrical circuit having impedance and capacitance but no resistance, the resonant frequency is described by the following familiar equation:

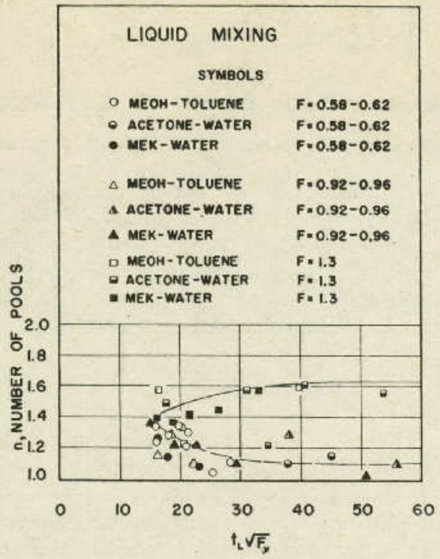


Fig. 3. Liquid mixing on bubble-cap tray.

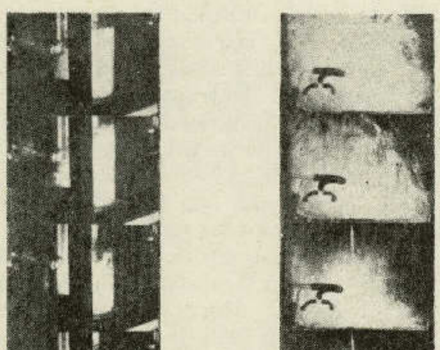
$$2\pi f = \frac{1}{\sqrt{L_i C}} \qquad (5)$$

Equation (5) relates the resonant frequency in a classical Helmholtz resonator to the inductance and the capacitance. For an acoustical system the inertance is analogous to the inductance in an electrical circuit. Richardson (7) shows that the inertance can be represented as

$$\text{inertance} = \frac{\rho_V l}{S'} \qquad (6)$$

Likewise the capacitance is expressed by

$$\frac{1}{C} = \frac{\partial p}{\partial V} = \frac{c^2 \rho_V}{V} \qquad (7)$$



Sieve tray Bubble-cap tray

Fig. 4. Liquid pulsations on a bubble-cap and on a sieve tray.

Equation (4) is a combination of Equations (5), (6), and (7) and expresses the resonant frequency acoustically when all the inertance (inductance) is concentrated in a small duct and the capacitance is in the entire body of the vessel.

Equation (4) could not be expected to describe the pulsation frequency in a distillation tower because no account has been taken of the coupling action of the liquid and gas flow rates. In distillation towers the vapor while bubbling through the liquid transmits part of the kinetic energy to the liquid. For a simple harmonic oscillator, the frequency of vibration is directly proportional to the velocity of motion; therefore, the kinetic energy would be proportional to the square of the frequency. Conversely, the frequency would be proportional to the square root of the kinetic energy. Since a coupling action or transferring of kinetic energy exists between the liquid and gas phases, correction for this action might logically be made by use of a ratio of the kinetic energies of the two phases. Accordingly, if this action be looked upon as a capacitance or ratio of inertial forces, Equation (4) may be rewritten as

$$f = k\frac{c}{2\pi}\sqrt{\frac{S}{lV\left[\frac{(mu^2)_V}{(mu^2)_L}\right]}} \qquad (8)$$

or, written on a unit volume basis, as

$$f = k\frac{c}{2\pi}\frac{F_L}{F_V}\sqrt{\frac{S}{lV}} \qquad (9)$$

The term k in Equations (8) and (9) may be looked upon as a proportionality constant, the numerical value of which was found to be 2.5 ± 0.2.

EQUIPMENT AND PROCEDURE

The bubble-cap tower used for the frequency studies, shown diagrammatically in Figure 1, had five rectangular trays and nine 1½-in. bubble caps placed on a square spacing. The sieve-tray unit, shown in Figure 2, had three trays and was connected to a 5-hp. centrifugal blower. The tray perforations consisted of $\frac{5}{16}$-in.-diameter holes on 1⅛-in. triangular centers. The pertinent dimensions of the two towers are given in Table 1.

Table 1. Dimensions of Towers

	Bubble-gap tower	Sieve-tray tower
V	12.5 cu ft.	9.56 cu. ft.
l	27.0 ft.	37.5 ft.
S	0.124 sq. ft.	0.0477 sq. ft.
A	0.615 sq. ft.	0.815 sq. ft.
S/lV	0.000368, 1/sq. ft.	0.0001325, 1/sq. ft.

For the bubble-cap tower, steam-water and acetone-water (95 mole % acetone) were separately run in the pulsating region at several flow rates. The frequency, measured visually through the glass window, was observed to decrease with increasing gas and liquid velocities (or F factors). The column was run at total reflux, and hence the liquid and vapor flow rates were not independent of each other.

The sieve-tray tower was operated only on the air-water system. Here the liquid flow rate was maintained constant, and the air velocity was varied.

RESULTS AND DISCUSSION

Table 2 gives the results of the frequency measurements on the bubble-cap and sieve-tray towers. All the factors in Equation (9) were known or were measured, and the value of k was determined.

Calculation of the F factor for the liquid is based on a clear-liquid–height measurement. One leg of a manometer was mounted flush in the floor of the tray; the other leg was open to the vapor space above the tray. The manometer itself was filled with the liquid on the tray, and its reading was thus in terms of clear liquid (free from vapor bubbles). The manometer reading reduced the head of the total liquid and bubbling mass to an equivalent height if only clear liquid were traveling across the tray. The resulting value for F_L is very sensitive to the clear-liquid–height measurement. Furthermore, when the frothing mass on the tray is in oscillatory motion,

Table 2. Pulsation-frequency Tests

	u, ft./sec. (active area)	L, gal./min.	T, °C.	Z_c, ft. of liquid	F_V	F_L	c, ft./sec.	f, measured cycles/sec.	k
Bubble-cap tower									
Steam-water	5.24	0.87	104	0.20	0.99	0.12	1,585	1.66	2.7
	6.26	1.04	104	0.20	1.19	0.15	1,585	1.51	2.5
	7.30	1.21	104	0.21	1.39	0.16	1,585	1.42	2.5
	8.73	1.45	104	0.22	1.66	0.19	1,585	1.39	2.5
Acetone-water (95% acetone)	2.78	1.52	60	0.22	0.87	0.18	934	1.44	2.4
	3.30	1.81	60	0.23	1.03	0.21	934	1.37	2.3
	4.50	2.46	60	0.24	1.41	0.27	934	1.34	2.4
Sieve-tray tower									
Air-water	6.28	1.30	25	0.06	1.78	0.37	1,118	1.11	2.6
	6.45	1.30	25	0.06	1.82	0.37	1,118	1.09	2.7
	7.21	1.30	25	0.06	2.04	0.37	1,118	0.99	2.6

the manometer reading gives a damped average value for Z_c. The value for Z_c reported in Table 2 is a rather crude time-averaged clear-liquid height. The variation of k shown in Table 2 probably results from inaccuracy in the measurement of Z_c.

The agreement of the data with Equation (9), as shown by the constancy of k in Table 2, is striking in view of the range of variables studied, especially since two totally different pieces of apparatus were involved.

As yet it has not been possible to predict under what conditions the oscillations would be initiated; however, several qualitative observations can be made. The first is that the oscillations have not been observed at low mass-vapor rates [G = 700 lb./(hr.)(sq. ft.)] in either the sieve tray or the bubble-cap tray. Oscillations occurred at lower mass-vapor rates in conjunction with the bubble-cap tray than with the sieve tray, possibly because of the particular trays used. In a study of perforated-plate performance, McAllister, McGinnis, and Plank (*5*) found that the oscillation point was coincidental with the *weep* point for plate thickness of $\frac{1}{16}$ in. and greater. For thin plates, 0.029 in. thick, the oscillation point was at a gas velocity much higher than the weep point. The weep point here refers to the point where all the holes in the perforated plate become operative (*2*), and it is usually considered to be the beginning of the normal operating range of the sieve tray. The oscillation point refers to the minimum gas velocity at which the oscillation is sustained for a given liquid-flow rate. McAllister, et al. (*5*), also found that the mass-flow rate of the vapor at the oscillation point decreased as the clear-liquid height on the tray increased. Presumably, the tray dimensions, the relative vapor and liquid velocities (or F factors), and possibly some of the physical properties of the fluids would be among the variables expected to determine when the pulsations would begin.

Another observation that may be pertinent is that in both the columns studied the liquid flow on successive plates was reversed. For this type of system the oscillation was found to be one-half cycle out of phase on succeeding trays. If the flow pattern were such that the liquid flow was all in the same direction across the plate on successive plates, no prediction is offered as to how oscillations would occur. The pulsations, however, are to be expected. No prediction is offered for split-flow plates or other channel-flow plate designs.

Preliminary tests, with a small unit with perforated stages, have indicated that oscillating behavior also occurs in fluidized beds where solid and gas phases are in contact. The mechanism of correlation must be slightly different, however, since there is no actual flow of the solid phase. Further work along this line is forthcoming.

CONCLUSIONS

In plate towers oscillation of the frothing mass may occur with characteristic frequencies. The oscillation of the liquid on the tray is perpendicular to the direction of the flow of the liquid. The frequency of the pulsation is a function of the vapor and liquid F factors, the velocity of sound in the vapor, and the dimensions of the systems. The study reported here includes data on a bubble-cap tower operating as a distillation tower and on a sieve-tray contacting unit in which air is pumped through the system with a blower. The oscillating behavior of the system is thought to apply in any type of plate tower where the vapor is forced to bubble through the liquid. The oscillation on bubble-cap trays and sieve trays of the type studied here is a resonance which is fundamentally acoustic in nature.

ACKNOWLEDGMENT

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R. W. Bondurant, Jr., and D. V. Knight, at one of the authors' suggestion, presented a preliminary paper on the subject of the pulsations in the sieve-tray and bubble-cap–tray towers during the Southern Regional Conference of Student Chapters of the A.I.Ch.E. at the University of Tennessee, Knoxville, on March 21 to 23, 1957.

Helpful suggestions, especially in the matter of coupling effects of the vapor and liquid kinetic energies, were made by Dr. F. W. Lancaster, Department of Physics, North Carolina State College, Raleigh.

NOTATION

A = active tray area, sq. ft.
B = ratio of the slope of the operating line to the slope of the equilibrium line
b = length of the liquid travel
C = capacitance
c = velocity of sound in the fluid, ft./sec.
f = frequency of pulsation, cycles/sec.

$$F_V = \sqrt{(\rho u^2)_V} = \sqrt{\left(\frac{mu^2}{v}\right)_V} = \sqrt{\left(\frac{K.E.}{v}\right)_V}$$

$$F_L = \sqrt{(\rho u^2)_L} = \sqrt{\left(\frac{K.E.}{v}\right)_L}$$

k = an empirical constant equal to 2.5 ± 0.2 (Table 2)
K.E. = kinetic energy, ft.-poundals
l = length of system, (*a*) sieve column: length of tower plus length of pipe plus twice the circumference of the blower; (*b*) bubble-cap column: length of reboiler to liquid level plus length of piping (containing vapor) plus tower length plus length of condenser
L = liquid rate, gal./min.
L' = liquid rate, cu. ft./sec.
L_i = inductance
m = mass, lb.
n = number of well-mixed pools (*3*)
p = pressure
ρ = density, lb. mass/cu. ft.
S = bubble-cap slot area, or hole area (sieve tray) per plate, sq. ft.
S' = cross-sectional area of small duct, sq. ft.
t_L = time of liquid contact, sec. [defined by Equation (3)]
u_L = average liquid velocity, ft./sec. $= L'/Z_c W$
u_V = superficial linear vapor velocity based on active tray area, ft./sec. $= w/\rho_V A$
v = volume of fluid, cu. ft.
V = total volume of distillation towers plus volume of vapor piping including condenser and reboiler, cu. ft.
W = width of tray perpendicular to liquid travel
w = weight rate of vapor flow, lb./sec.
y = vapor composition—mole fraction
y_{nb}^* = vapor composition in equilibrium with liquid samples taken at certain locations on the tray
Z_c = equivalent clear-liquid height of fluid on the active tray, ft.

Subscripts

L = liquid
V = vapor
n = plate number

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