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Oscillating Behavior on Distillation Trays-II

This paper describes an extension of an earlier study on oscillations which can develop on distillation trays. The oscillations take the form of violent lateral movements of the gas/liquid biphase, and they are generally undesirable for good column performance. It has been found that lower density gases need higher velocities to initiate oscillation, and vice versa for higher densities. The predictive method for the onset of oscillations proposed previously appears to remain valid for the range of gas density covered, and for small hole size trays. The presence of oscillations has been shown to increase weeping significantly.

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SCOPE

The objective of this work was to extend the study by Biddulph and Stephens (1974) of the phenomenon of oscillations on sieve trays. The dimensionless group which was proposed earlier as a criterion for the onset of oscillations was based on the work of Hinze (1965) and on dimensional analysis. The group did appear to have consistent critical values for full-wave oscillation and half-wave oscillation for the results then available. However all these results were on the system air/water, and so the dependence on gas density could not be confirmed. In this extension of the work, the apparatus was modified to allow various gas mixtures to be used. This was achieved by converting the open system used previously into a sealed, closed-circuit system. Mixtures of helium and air of various compositions were used to obtain densities lower than that of air. Mixtures of carbon dioxide and air were used

to obtain densities greater than air. By this means a range of gas density of 0.79 kg/m^3 up to 1.8 kg/m^3 was obtained. All these mixtures were recirculated around the apparatus at a great enough velocity to initiate full-wave oscillation.

The apparatus was further modified to enable the amount of liquid weeping through the upper tray to be measured. Weeping was studied as a function of gas velocity, starting from just above the dumping point up to high velocities well into the half-wave oscillating range. Weeping was also measured over the same range of conditions, but with the oscillations prevented by the same baffle system as has been described earlier.

The behavior of sieve trays with small hole sizes has been studied, with particular attention to mixing and oscillations.

Some qualitative observations are reported on the nature of weeping and on stagnant areas.

CONCLUSIONS AND SIGNIFICANCE

The same two types of oscillation, full-wave and half-wave, as were previously observed have been noted over a range of gas density. The lower critical gas velocity, that corresponding to the definite presence of full-wave oscillation, has been measured over the range of gas density. The mixing characteristics of the tray have been measured, and the results indicated that the extent of back mixing did not depend on gas density, within the range studied. It also appears from these results that full-wave oscillations did not significantly increase the amount of back mixing in the direction of liquid flow. The finding that gas density itself does not appear to have a significant effect on eddy diffusivity gives confidence in applying correlations for eddy diffusivity developed from air/water studies to other systems.

The previously proposed critical dimensionless group defined as

$$B_s = \frac{V \epsilon h_f \rho_g}{g d^3 \rho_L \overline{\alpha}}$$

has been calculated for all the results in the gas density study. The critical value of 0.5×10^{-5}, below which oscillations do not occur, appears to hold over the range studied. This gives some confidence in applying the method to other systems and supports the conclusion from the earlier study that columns operating at reduced pressures will show an increased tendency to oscillate.

It was observed qualitatively in the earlier work that full-wave oscillation appeared to increase the amount of liquid weeping through the tray. Each time a peak hits the wall, or the centerline peak forms, a spurt of liquid weeps down through the holes beneath the peak. By suitably modifying the equipment, it has been possible to measure the amount of liquid weeping through the tray over a range of gas flow rates. It was found that full-wave oscillation can increase weeping by 150%, and this relative increase persists up into the half-wave oscillating region. Thus it has been demonstrated that in addition to increasing entrainment as measured in the earlier study, oscillations also have the undesirable effect of increasing weeping. It was also noted that on decreasing the gas flow below the weep-point (Mayfield et al., 1952), the amount of weeping liquid appeared to approach a limiting value until eventually at very low velocities all the liquid dumped through the tray.

This study also includes some work on sieve trays with small hole sizes. These trays are similar to those often used in distillation columns in air-separation plants. It appears that there may be a slight reduction in the value of eddy diffusivity in the case of trays with very small hole sizes. The trays oscillate in a similar way to trays with larger holes, and the predictive criterion appears to remain valid.

Qualitative confirmation of the observations of Zanelli and Del Bianco (1973) on variations in hydrostatic head and their effect on weeping was obtained. In addition, it has been observed that full wave oscillations remove the stagnant zones on trays, near the column walls.

The performance of distillation trays under various conditions continues to attract attention, particularly under circumstances which cause unsatisfactory behavior. One phenomenon which has been observed and studied over a number of years is biphase oscillation. It has been found that under certain conditions of operation the liquid/vapor biphase on a distillation tray, instead of being stable with an approximately constant froth height over the entire tray, can begin to make violent lateral movements across the direction of liquid flow.

Foss and Gerster (1956), McAllister and Plank (1958), McAllister et al. (1958), and Barker and Self (1962) all reported the situation where a large peak strikes one wall of the column at the same instant as a trough appears at the opposite wall. This has also been observed by Zanelli and Del Bianco (1973). All these earlier studies used trays of fairly small dimension, up to about 0.3m in diameter.

A recent paper by Biddulph and Stephens (1974) has extended the range of observation of this phenomenon by studying a larger column of diameter 0.69 m. The same phenomenon of violent oscillation has been observed and is defined as half-wave oscillation since the wave length appears to be twice the column diameter. This occurs at high gas rates through the column. Biddulph and Stephens (1974) also observed a related phenomenon which occurs at lower gas rates and is defined as full-wave oscillation. In this case, peaks in the biphase strike the two side walls of the tray simultaneously with a trough at the center. The peaks then move together and meet at the center line of the tray, and the rhythmic back and forth motion is continued. The wave length appears to be equal to the column diameter. This was shown to be undesirable because of the severely increased entrainment levels which resulted. It was also noted that weeping appeared to be increased by the presence of oscillations, but no quantitative measurements were made. The detailed theoretical approach of Hinze (1965) was used, together with dimensional analysis to develop a dimensionless group which would be expected to have critical values for the onset of full-wave, and half-wave, oscillation.

This group is

$$B_s = \frac{V \epsilon h_f \rho_g}{g d^3 \rho_L \overline{\alpha}}$$

The experiments indicated that a value of 0.5×10^{-5} was critical for full-wave oscillation and 2.5×10^{-5} for half-wave oscillation. These values are the minimum values, below which the appropriate type of oscillation is not observed. The use of other workers' earlier results where possible indicated that this critical group did appear to be valid over a range of column diameters.

On the basis of the suggested criterion it was concluded that columns operating at atmospheric pressure or above, and of diameter 1.0m or greater are unlikely to oscillate. However, if the critical group is still valid for a range of values of gas density, then larger diameter columns operating at reduced pressure, with higher vapor velocities, might oscillate.

The object of the present work has been to study the phenomenon of oscillation further and to attempt to establish whether the suggested criterion is likely to be valid for different gas densities, and for sieve trays with small hole sizes. These trays are similar to those commonly used in the distillation columns of air separation plants.

In addition, the influence of oscillation on weeping has been studied and quantitative measurements made under oscillating and nonoscillating conditions. Some general observations of sieve tray behavior have been made and are reported.

EXPERIMENTAL APPARATUS

The apparatus used in this study is basically the same as that described by Biddulph and Stephens (1974). However, two different modified forms of the apparatus have been used in this work, and so the basic apparatus will be described briefly, with the modifications noted.

A large centrifugal blower (A) driven by a 15 H.P. motor through a variable speed hydraulic gear box blows air up through the 0.69-m diameter column. The column is constructed from clear polyvinylchloride and two sieve trays are located in the column, with a tray spacing of 0.61 m. The trays are either perpsex or aluminum. They are round with segmental outlet weirs 0.47 m long. The outlet downcomer area is 0.028 m^2. Water is pumped from a 0.45 m^3 tank (D) by means of a 2 H.P. centrifugal pump into the column through the 7.6 cm diameter pipe (G). The flow rate is measured using either the rotameter (F) or an orifice meter. The water was either returned to the tank or straight to drain.

Salt injection from a tank (P) and through an injector tube (S) is possible for mixing studies.

Figure 1a shows the equipment in its modified form for the gas density studies. In order to use gases other than air, it was necessary to make the equipment a closed system rather than the open system used in the previous air/water studies. Thus the gas outlet from the top of the column, which had previously been simply open, is now via a conical section into a duct 20 cm in diameter, leading down to the inlet to the blower. The gas in the system is thus circulated around. Great care was taken to seal the entire apparatus, including the blower bearings. Helium/air mixtures and carbon dioxide/air mixtures were used to obtain lower and higher density gases, respectively. The gas velocity was measured using a pitot tube at the blower outlet with a suitable correction for gas density.

Figure 1b shows the equipment in the form used to study weeping. The annular trough (B) with a shallow wire mesh cone which was formerly used to collect the entrained droplets is now moved below the upper test tray. This catches the liquid which weeps through the upper tray and the collected liquid passes out through a 2-cm diam. pipe through the column wall. Obviously it is necessary to avoid any entrainment from the lower tray. This is achieved by diverting the water from the bottom of the downcomer from the upper tray directly to drain through a 7.6-cm diam. pipe passing through the column wall. This means that the lower sieve tray is dry, and this makes it easy to confirm that the shallow wire mesh cone is catching all the liquid weeping through the upper tray. The weeping liquid is collected over a given time interval.

EFFECT OF GAS DENSITY

One of the variables included in the criterion for oscillation initiation proposed in the earlier paper is gas density. The results previously reported were all on the system air/water. Obviously, differences in gas density occur from system to system, and it is desirable to attempt to ascertain whether the effect of

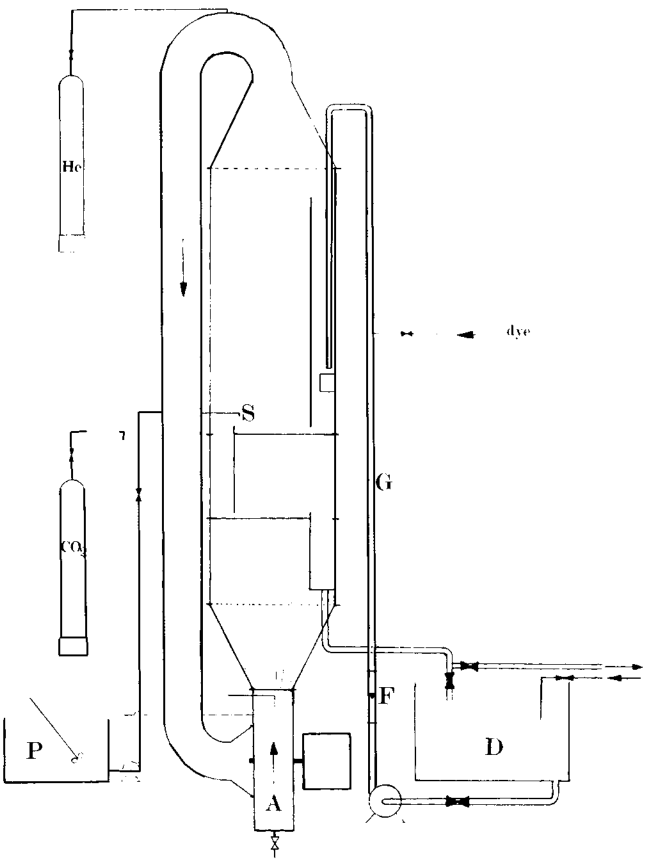

Fig. 1a. Closed circuit apparatus. Tray details:
Tray 1 6.4 mm holes, 10% free area
Tray 2 6.4 mm holes, 5% free area
Tray 3 3.0 mm holes 12.8% free area
Tray 4 1.75 mm holes, 7.7% free area

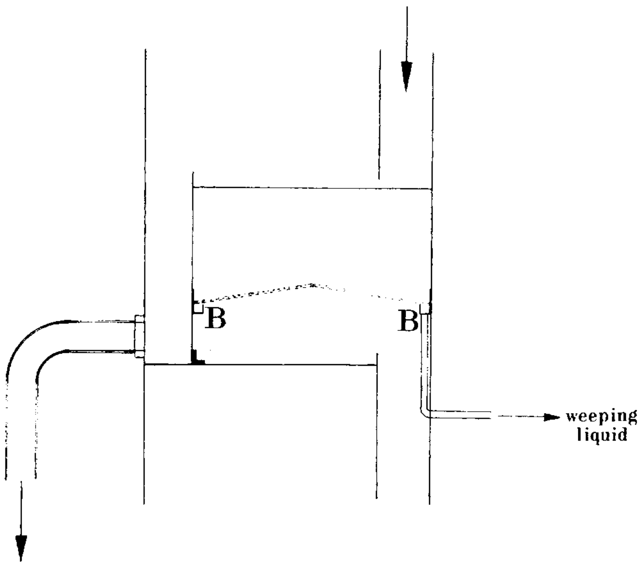

Fig. 1b. Weeping modification

gas density is as proposed. The criterion $B_s = \frac{V_\epsilon h_f \rho_g}{g d \, \rho_L \bar{\alpha}} = 0.5 \times 10^{-5}$ for full-wave oscillation was based on an extension of the work of Hinze (1965). This suggests that for systems with lower values of gas density, a higher initiation velocity would probably be observed together with a possibly increased value of ϵ, the eddy viscosity.

In order to study the effect of gas density, the apparatus was used in its closed-circuit modified form. (Figure 1a). Gas densities both lower and higher than that of air were obtained by replacing some of the air contained within the apparatus with a suitable gas.

Reduced gas densities were obtained by passing helium into the apparatus from a cylinder. In fact slightly impure helium, known as *balloon-gas*, was used for economical reasons. The gas was passed into the apparatus through a control valve into the highest point in the apparatus at the top of the recirculating duct. An outlet at the bottom of the apparatus was opened and a rotameter connected in order to observe the rate of outflow of air during filling. In this way, an estimate could be made of the length of filling time required to achieve a given desired density. Densities down to 0.79 kg/m³ were studied using this technique.

When sufficient time had been allowed the helium was shut off, but the cylinder was left connected to the apparatus to maintain a small make up stream during a run. The outlet was closed.

The procedure for a run was then as follows: The blower was started up and allowed to run at fairly low speed for 5 min. to ensure that the helium/air mixture was thoroughly mixed. The speed of the blower was then increased until a gas velocity high enough to prevent excessive weeping was achieved. The water pump was then started, and water was pumped into the column.

The biphase was observed carefully and the blower speed increased until definite full-wave oscillation occurred on the tray. The salt solution injection was then commenced, and samples were taken in order to estimate the eddy diffusivity in the same way as described in the earlier paper. The clear liquid head, froth height, and pressure drop readings were noted. A small helium input was usually required to maintain the density constant. This was set by observing the reading on the inclined manometer connected to the pitot tube at the outlet from the blower. With the blower speed remaining constant throughout the run, the helium bleed in was adjusted to keep the manometer reading constant.

The density of the mixture in the apparatus was measured by simply filling a 20-ml syringe from an outlet immediately above the blower. This syringe was then very accurately weighed, and this weight compared with the weight of the syringe. A simple calculation gives the gas density. The density measurement was made at the start of a run, halfway through, and at the end of the run. Only runs which had a constant density were recorded.

Gas densities greater than that of air were obtained by using carbon dioxide gas. This was added from a liquid carbon dioxide cylinder at a point near the bottom of the apparatus. An outlet at the top of the apparatus allowed the air to escape during filling, and this was measured to give an estimate of filling time required, as in the case of helium. The procedure was the same as that for a run using helium except that a much greater addition of gas during a run was required because of the absorption of the carbon dioxide by the water. Carbon dioxide was added from the cylinder through a heated valve and line to prevent freezing. In addition many small pieces of solid carbon dioxide were put into the water feed tank to reduce the amount of absorption in the apparatus. Again the inclined manometer on the pitot tube was maintained constant during a run and the density measured. Gas densities up to 1.8 kg/m³ were obtained by using this method. Thus a range of gas density from 0.79 up to 1.8 kg/m³ was studied. This is a smaller range of gas density than the range of commercial densities, but it enables the validity of the criterion to be studied.

RESULTS

It was found that full-wave oscillation could be obtained over the entire range of gas densities covered. The gas velocity was calculated from the pitot tube reading, allowance being made for the gas density. The detailed results are shown in Table 1. These were all on Tray 1 with a liquid rate of 5.5×10^{-3} m³/s (m of weir) and a weir height of 7.6 cm. The fluids were at room temperature and atmospheric pressure on all these runs.

In all these runs the clear liquid head on the tray was about 3 cm, the froth height was 20 to 23 cm, and the overall tray pressure drop was about 10 cm of water. No variation with density and velocity was observed although any variation would have been obscured by the fluctuations present during full wave oscillation. It will be seen in the later results that full-wave oscillation did occur at lower froth heights when other trays were studied.

TABLE 1. GAS DENSITY RESULTS

Gas density, kg/m³	Full-wave oscillation gas velocity, m/s	Eddy diffusivity, m²/s	$B_s \times 10^5$
0.787	1.9	0.0144	0.74
0.797	1.73	0.012	0.66
0.84	1.86	0.013	0.81
0.92	1.61	0.010	0.61
0.97	1.64	0.011	0.69
1.00	1.64	0.011	0.70
1.08	1.60	0.010	0.71
1.13	1.59	0.0099	0.84
1.277	1.65	0.0093	0.74
1.527	1.38	0.0072	0.67
1.557	1.35	0.007	0.64
1.642	1.28	0.0063	0.57
1.662	1.37	0.0081	0.83
1.77	1.29	0.0065	0.70
1.802	1.28	0.0065	0.66

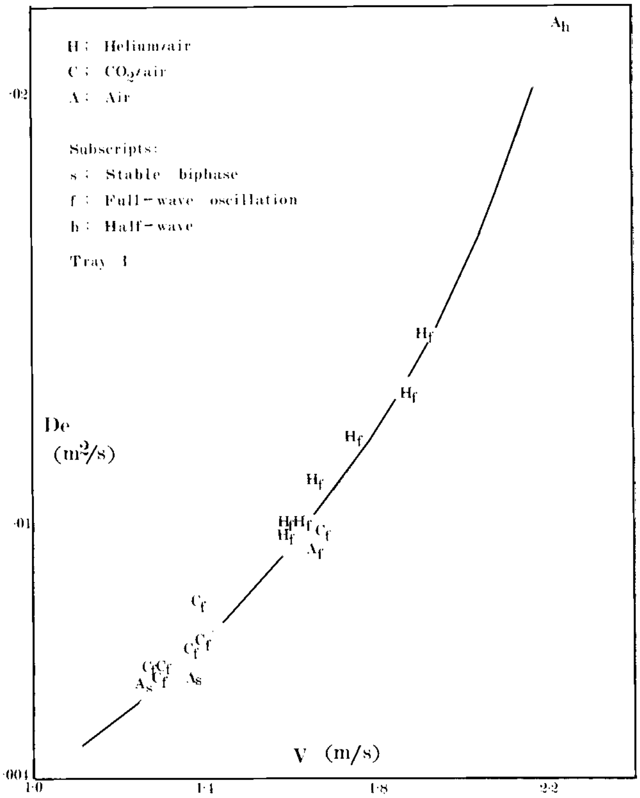

Fig. 2. Dependence of eddy diffusivity on superficial vapor velocity.

The results are firstly reviewed to determine whether gas density, within the range studied, had any effect on the mixing on the tray. Figure 2 shows the eddy diffusivity *De* plotted as a function of superficial gas velocity. The results in Table 1 are plotted, all full-wave oscillating conditions, together with runs 11, 17, and 13 from the earlier paper. These were half-wave oscillation and stable biphase, respectively. In addition, an extra run with a carbon dioxide/air mixture of density 1.58 kg/m^3 with a gas velocity well above the full-wave initiation velocity was plotted. It can be seen that all the points fall quite close to a smooth curve even though a higher density run may be oscillating at a velocity which allows a stable biphase for a lower density gas. This also indicates that full-wave oscillation did not have a noticeable effect on the eddy diffusivity; that is, it did not significantly increase the amount of back mixing in the direction of liquid flow.

The conclusion that gas density itself does not affect the values of eddy diffusivity, within the range studied, encourages the application of correlations for eddy diffusivity developed on air/water to other systems.

In calculating the value of B_s, the same assumption has been made as in the earlier paper. This is that the eddy viscosity ϵ is equal to the eddy diffusivity *De*.

It can be seen from Table 1 that the value of the critical dimensionless group B_s remained substantially constant in spite of the fact that the velocity for full-wave oscillation varied from 1.9 to 1.28 m/s corresponding to a variation in gas density from 0.787 to 1.802 kg/m^3. The results are plotted in Figure 3 in a similar form to that used in the earlier paper. In addition, a line is shown to illustrate the earlier results for a range of gas velocities using air/water.

Although there is some scatter due to the fact that all the runs were definitely above the initiation velocity, the results do appear to suggest that the criterion of $B_s = 0.5 \times 10^{-5}$ is valid for a range of gas densities in this column. This, together with the earlier results gives some confidence that the criterion is generally valid.

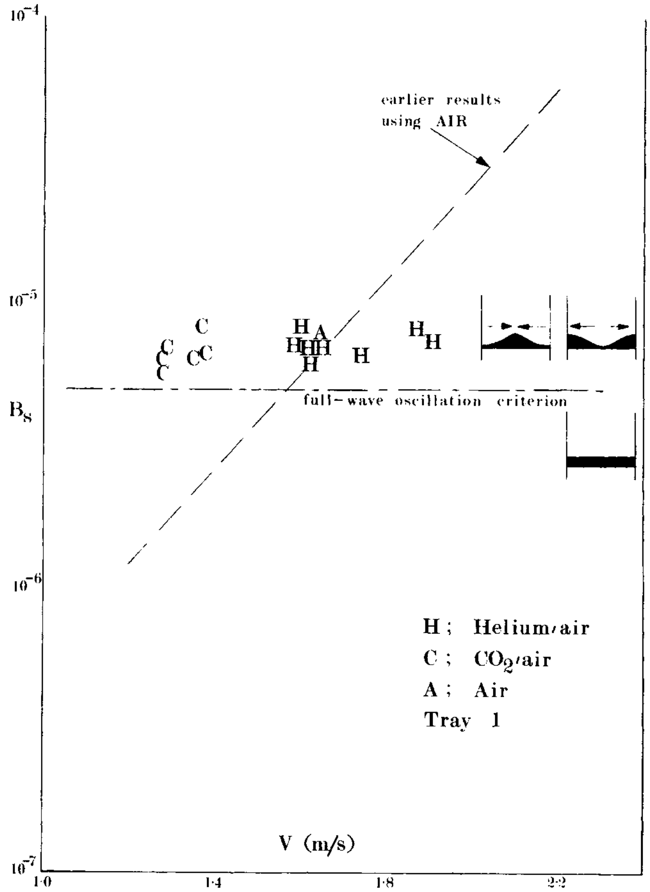

Fig. 3. Values of B_s for various gas densities.

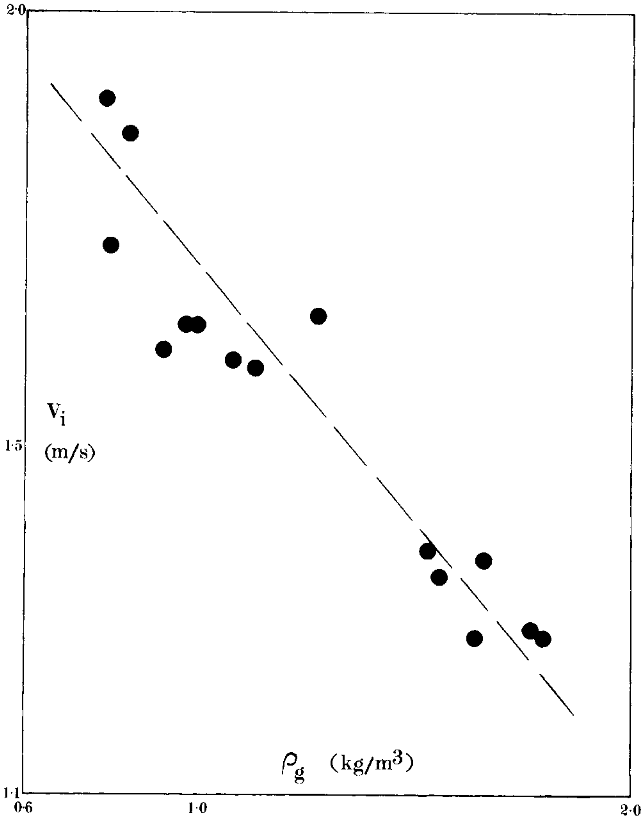

Fig. 4. Dependence of full wave oscillation velocity on gas density.

Figure 4 shows the results plotted as the full-wave oscillation velocity as a function of gas density.

The equations developed by Barker and Self (1962) for the prediction of the eddy diffusivity *De*, the clear liquid head h_L, and the froth height h_f from work on air/water on a sieve tray with 4.8-mm holes are as follows:

$$De = 0.0067V^{1.44} + 0.0922h_L - 0.0056$$
$$h_L = 0.024 + 1.74L^* + 0.372W - 0.012V$$
$$h_f = 0.0354 + 4.81L^* + 1.05W + 0.0384V$$

The constants are specific to S.I. units. The predicted values using these equations are used to predict a critical full-wave initiation velocity using a value of $B_s = 0.5 \times 10^{-5}$. The observed and predicted velocities are compared in Figure 5. The predictions tend to be somewhat low, by about 13% in the higher velocities of the low gas density runs. This is because the true initiation velocity was somewhat lower than the observed velocities in these runs. This effect was counteracted in the lower velocity runs by somewhat low predictions of the froth height. Thus these equations can be used to give a reasonably good estimation of the critical superficial gas velocity in a column.

OSCILLATIONS ON SMALL HOLE SIZE TRAYS

In order to extend the study of oscillations on sieve trays, trays with small holes similar to those used in distillation columns in air separation plants have been investigated. Tray 3 has 3-mm diameter holes on 8-mm hole spacing giving a free area of 12.8%. Tray 4 has 1.75-mm holes on 6-mm spacing, giving a free area of 7.7%. Both percentages are based on active area.

In all the runs, the mixing characteristics were studied using the salt injection technique described previously. The

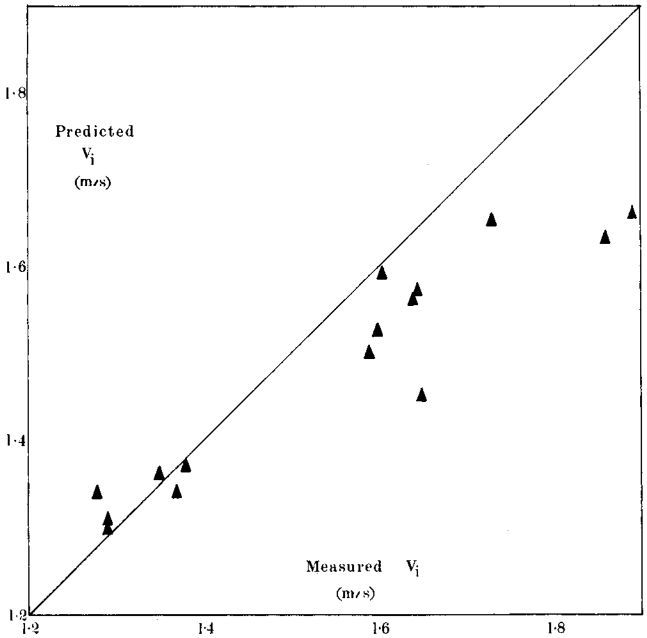

Fig. 5. Measured initiation velocities compared with predicted values.

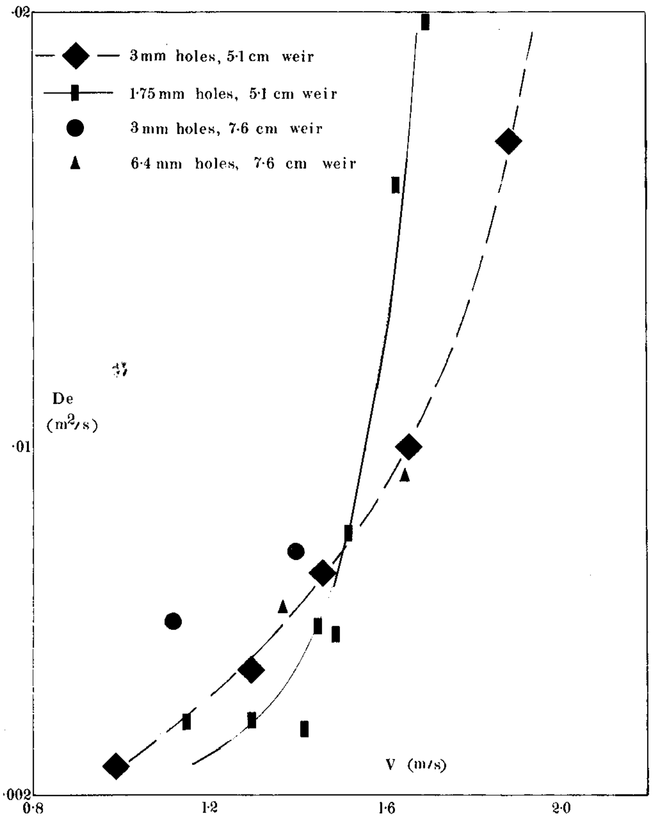

Fig. 6. Eddy diffusivity on small hole size trays.

results are shown in Figure 6. In the lower velocity region, the smallest hole size tray shows marginally lower values of eddy diffusivity *De* compared with the 3-mm tray. The results on the 3 mm tray are similar to those previously obtained on the 6.4 mm hole tray. On these trays, the eddy diffusivity shows sharp increases in the oscillating region.

The recent work of Pruden, Hayduk, and Laudie (1974) has indicated that hole size itself has little effect on measured tray efficiencies of 0.15-m diameter sieve trays. A slight improvement in efficiency was observed for smaller

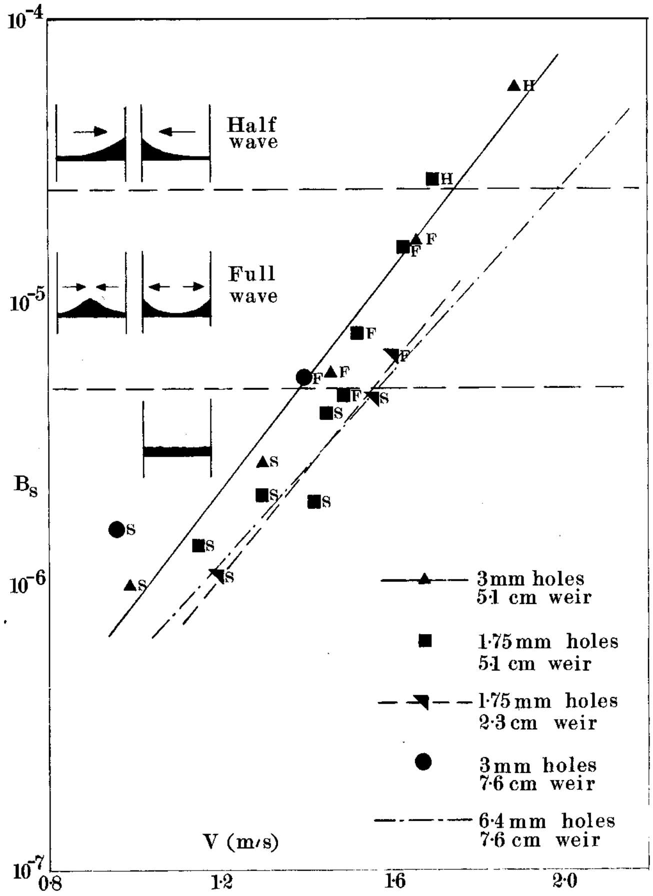

Fig. 7. B_s values for various trays.

hole sizes. Since the tray was operating with partial mixing, this improvement would be expected from the results obtained here which indicate that the back-mixing would be slightly less for the smaller hole sizes, leading to higher tray efficiencies. This effect probably partially explains the high efficiencies which are obtained on large diameter sieve trays with small hole sizes.

Trays 3 and 4 were studied with particular attention paid to the onset of oscillations. A range of outlet weir heights was used at a constant liquid rate. The air rate was raised progressively from the stable region up into the full-wave oscillating region. In all the runs the value of the dimensionless group B_s was calculated, and the values are shown in Figure 7. The earlier results on tray 1 are included. The critical regions are shown, and the results appear to confirm the validity of the criterion for the trays studied and the range of conditions covered. It can be seen that the critical gas velocity for full-wave oscillation varies from 1.4 m/s for a 7.6-mm outlet weir on the 3-mm hole tray to about 1.6 m/s for a 2.3-cm weir on the 1.75-mm hole tray. The results are tabulated in Table 2. The height of the outlet weir, varying from 7.6 cm to 2.3 cm had a marked effect on the full-wave oscillation velocity, greater gas velocities being needed for lower weir heights. This was also detected from the earlier results. This is predictable from the proposed criterion since the froth height appears in the numerator of the dimensionless group.

Tray 4, with a 2.3-cm outlet weir developed oscillations with a froth height of 17-cm compared with about 20-cm with a 5.1-cm weir. The velocity required was correspondingly higher for the lower weir height.

By taking the criterion of B_s equal to 0.5×10^{-5} for full wave oscillation, and using the conditions existing in the lower column of an air separation double column, it

Table 2. Oscillations on Small Hole Size Trays

Liquid flow, $m^3/(s)$ (m of weir) $\times 10^4$	Vapor vely, m/s	Weir ht., cm	Hole size, cm	% hole area	ΔP total cm H_2O	Liquid head, cm	Froth Ht., cm	Eddy diffusivity, De m^2/s	$B_s \times 10^5$	Biphase behavior
55	0.96	7.6	0.30	12.75	7.0	3.7	19	0.006	0.16	S
55	1.4	7.6	0.30	12.75	8.0	3.5	21	0.0076	0.54	F_i
55	0.99	5.1	0.30	12.75	6.0	2.8	16	0.0027	0.10	S
55	1.46	5.1	0.30	12.75	7.5	2.7	19	0.0071	0.56	F_i
55	1.3	5.1	0.30	12.75	6.5	2.7	17	0.0049	0.27	S
55	1.66	5.1	0.30	12.75	8.0	2.0	22	0.01	1.65	F
55	1.89	5.1	0.30	12.75	9.0	1.2	23	0.017	5.7	H
55	1.3	5.1	0.175	7.72	10.0	2.9	18	0.0037	0.21	S
55	1.52	5.1	0.175	7.72	13.0	2.5	20	0.008	0.78	F_i
55	1.49	5.1	0.175	7.72	12.0	2.6	19	0.0057	0.47	F_i
55	1.42	5.1	0.175	7.72	12.0	3.0	18	0.0035	0.2	S
55	1.15	5.1	0.175	7.72	10.0	3.3	17	0.0037	0.14	S
55	1.45	5.1	0.175	7.72	11.0	2.7	18	0.0059	0.41	S
55	1.63	5.1	0.175	7.72	14.0	2.5	20	0.016	1.57	F
55	1.7	5.1	0.175	7.72	16.0	2.4	22	0.020	2.7	H_i
55	1.2	2.3	0.175	7.72	9.5	2.1	13	0.0028	0.11	S
55	1.55	2.3	0.175	7.72	12.0	1.6	16	0.0047	0.47	S
55	1.60	2.3	0.175	7.72	13.0	1.5	17	0.0053	0.66	F_i

S = stable: F_i = full-wave initiation: H_i = half-wave initiation.

appears that only columns of less than 0.4-m would oscillate. Since these columns are usually much larger than this, possiby 3-m in diameter, there is no likelihood of oscillations developing. This is largely due to the low vapour velocities and low foam heights which are typical of these columns.

OSCILLATIONS AND WEEPING

In the earlier paper it was noted that the presence of full-wave oscillation on the tray appeared to increase the amount of liquid weeping through the holes. This extra weeping occurred beneath the wave peaks, both at the walls and along the center line of the tray. This has now been studied in detail for Tray 3.

The apparatus was modified to allow the weeping liquid to be collected and measured over a given time interval. The modifications are shown in Figure 1b, and have been described. Tray 3 was used with an outlet weir height of 7.6 cm. A series of runs was carried out starting from low air rates when heavy weeping was occurring from a stable biphase up to very high air rates when half wave oscillation was occurring and virtually no weeping was observed. The weeping results were calculated as (kg weeping liquid) per (kg of liquid flow across the tray).

In the earlier paper, a baffle system was described which had been developed to remove oscillations. This consisted of two vertical baffles made from expanded metal of about 55% open area. These baffles are placed in line with the direction of liquid flow, from the inlet weir to the outlet weir at 1/3 and 2/3 across the tray diameter. Thus the biphase runs parallel to these baffles, and so they do not interfere materially with the flow. However, they do completely prevent oscillations from developing and maintain an even stable biphase. The baffles are not solid since this would merely create closer reflecting surfaces for oscillations. The expanded metal allows restricted lateral movement through the baffle.

The baffle system was used in the earlier study to evaluate the effect of oscillations on entrainment levels above trays. In this study, they have been used to evaluate the amount of weeping which is due to the presence of oscillation. Thus, after the recent results on the unbaffled tray were completed, the baffles were installed, and a similar series of runs was carried out over a similar range of gas velocities. The results are shown in Table 3, all for a liquid rate of 5.5×10^{-3} $m^3/(s)$ (m of weir).

Table 3. Weeping Results

Unbaffled biphase		Stable biphase (Baffled)	
Air velocity, m/s	Weepage, kg/kg	Air velocity, m/s	Weepage, kg/kg
0.91	0.0195	0.86	0.0187
0.92	0.0179	0.98	0.0187
1.07	0.0187	1.21	0.0179
1.13	0.0164	1.38	0.0171
1.29	0.0187	1.44	0.0148
1.37	0.0249	1.50	0.0125
1.41	0.0304	1.64	0.0132
1.57	0.0280	1.69	0.0086
1.53	0.0327	1.71	0.0093
1.64	0.0304	1.83	0.0062
1.76	0.0156	1.87	0.0047
1.78	0.0171	2.02	0.0031
1.92	0.0093		
1.97	0.0093		

They are plotted in Figure 8. It can be seen that a considerable increase in weeping is observed when full-wave oscillations are present. As the gas rate is progressively raised into the half-wave region, the amount of weeping decreases due to the increased gas velocity preventing even localized weeping to some extent. However on this tray, even in the half-wave region, the amount of weeping is still greater than with a stable biphase under the same conditions. The predicted weep-point by the method of Hughmark and O'Connell (1957) and by the method of Mayfield (1952) is 1.2 m/s. Thus on this tray, there is a significant amount of weeping at gas velocities above the weep-point. The full wave oscillation on the tray occurred just above the weep-point, where a noticeable amount of weeping still occurs from a stable biphase. However, the

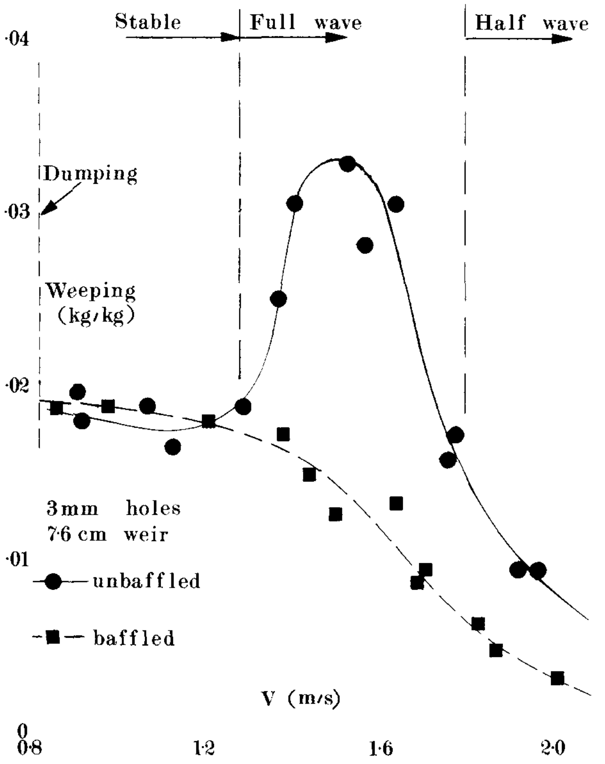

Fig. 8. Effect of oscillation on weeping.

presence of full wave oscillation has increased the amount of weeping by a factor of 2.5. The same relative increase in weeping is apparent at the high velocities in the half-wave oscillation region.

The form of the curves shows a flattening at very low gas rates. Even as the gas rate was lowered down almost to the point where liquid is dumped down off the tray, the actual amount of weeping liquid did not seem to increase. This indicates that there may be a limiting weep rate which is possible with gas still passing up through the tray. This can be exceeded when very extensive local weeping is present on some parts of the tray, that is, almost local dumping. The limiting value for overall general weeping for this set of conditions appeared to be about 0.019 kg/kg. This part of the curve was the same both with and without baffles present, indicating that the presence of baffles did not significantly change the operation of a tray in the stable biphase region. When the gas rate got down to about 0.8 m/s, the liquid dumped off the tray.

SOME GENERAL OBSERVATIONS ON TRAY BEHAVIOR

Recent work by Porter, Lockett, and Lim (1972) and by Bell (1972) has indicated the presence of partially stagnant zones of biphase near the walls of the column. These stagnant zones were observed in the present study on Tray 3 by means of a dye injection technique. While the tray was operating with a stable biphase, a stream of naphthalene black dye was injected continuously into the inlet water stream by means of a small centrifugal pump. After a period of injection, the entire biphase became evenly colored. The dye injection pump was stopped and the process of color removal from the biphase by the fresh water observed. Areas of color corresponding to Porter's region II were observed to persist a significant length of time after the centre of the tray (Porter's region I) had cleared.

The same experiment was carried out with the tray operating with full-wave oscillation present. In this case, the entire tray cleared at the same time, indicating as would be expected, that the lateral movement of the biphase eliminated the partially stagnant zones.

Recently Zanelli and Del Bianco (1973) have reported a study of perforated plate weeping. A single hole in the perforated plate was studied and drop frequencies noted. They observed variations in hydrostatic head on the tray, and noted waves of frequency 2.5 to 3.3 hz and wavelength of 10 to 20 cm, in addition to half-wave oscillations. They concluded that the hydrostatic head variations were present over the entire range of operating conditions, with an amplitude increasing as the gas flow rate increased.

The trays used in the present study were closely observed in order to determine whether the same effect could be seen. When the underside of the tray was observed under conditions of stable biphase with weeping, the weeping did appear to come from localized groups of holes, in spurts. These localized groups varied around the tray, and appeared to be 10 to 20 cm apart, tending to confirm the observation of Zanelli and Del Bianco (1973). When the gas flow rate was raised, and full-wave oscillation occurred, all the weeping came from the major peaks, at the walls and along the center line of the tray. These lateral movements obviously overrode any hydrostatic head variations which may have been present.

The baffle system described earlier was re-installed and the mechanism of weeping at higher flow rates observed. At flow rates well into the full-wave oscillating region and above, such weeping as did occur appeared still to come from groups of holes about 10 to 20 cm apart. Thus the hydrostatic head variations reported by Zanelli and Del Bianco (1973) did appear to be still present at gas flow rates up to 1.8 m/s which would have given rise to violent oscillations if the baffles had not been present. This work tends to confirm the observation of hydrostatic head variations.

CONCLUSIONS

The earlier experimental study of oscillations on distillation trays has been extended. The effect of gas density on oscillation initiation has been investigated and the previously proposed criterion appears to be valid over the range of gas density studied. This tends to support the conclusion from the earlier study that columns operating at reduced pressure may show an increased tendency to oscillate due to the higher vapor velocities. However, further work is desirable to extend the range of gas density.

It is of interest to note that with air/water in this column, full-wave oscillations occur at about 52% of the air velocity predicted by the Fair (1963) model for flooding with 0.6 m tray spacing. Half-wave oscillations occur at about 67% of flooding.

The effect of oscillation on weeping has been measured, and it has been found that weeping can be increased by 150% compared with weeping from a stable biphase. This comparison was made possible by the use of baffles described earlier by Biddulph and Stephens (1974).

Sieve trays with small hole sizes have been studied and have been found to oscillate. The back-mixing on these trays has been measured, and there appears to be slightly reduced mixing on trays with smaller hole sizes.

Weeping appears to take place through small groups of holes around the tray. This confirms the observation of Zanelli and Del Bianco (1973) of variations in hydrostatic head. These variations take place in a stable biphase over a wide range of conditions.

NOTATION

B_s = dimensionless group based on superficial vapor velocity

De = eddy diffusivity, m^2/s
d = column diameter, m
F = full-wave oscillation
H = half-wave oscillation
h_f = froth height, m
h_L = clear liquid head, m
L^* = liquid rate, $m^3/(s)$ (m of weir)
S = stable biphase
V = superficial vapor velocity, m/s
V_i = full wave oscillation velocity, m/s
W = weir height, m
$\bar{\alpha}$ = h_L/h_f = relative froth density
ϵ = eddy viscosity, m^2/s
ρ_g = gas density, kg/m^3
ρ_L = liquid density, kg/m^3
g = acceleration due to gravity, m/s^2

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Thermodynamic Consistency Using Orthogonal Collocation or Computation of Equilibrium Vapor Compositions at High Pressures

The numerical method of orthogonal collocation is used within a thermodynamically consistent framework to calculate equilibrium vapor compositions from P-T-x data for binary systems. The method may be used for isothermal or isobaric data in both the normal liquid and in the critical region, and it applies to any choice of standard states.

To use the method it is necessary to have experimental or estimated values of vapor phase fugacity coefficients for both components in the mixture and liquid molar volumes (isothermal case) or heats of mixing (isobaric case). If vapor composition data are available, each set of P-T-x-y data may be checked for thermodynamic consistency by comparing y (experimental) with y (calculated). Illustrative calculations are given. The method is shown to provide an excellent procedure for obtaining Henry's constants from P-x data for systems with one noncondensable component.

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It has been known for three generations that the Gibbs-Duhem equation can be used (1) to test complete vapor-liquid equilibrium data for consistency, or (2) to extend incomplete vapor-liquid equilibrium data.

Hundreds of papers have been written on this subject but almost all deal with low-pressure data. Many deal with the area test which Van Ness et al. (1973) have shown to be unsatisfactory. A proper test is to use only some of the data and to predict the rest using the Gibbs-Duhem

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