Residence Time Distribution of the Dispersed Phase in a Spray Column

RUTH LETAN and EPHRAIM KEHAT

Technion, Israel Institute of Technology, Haifa, Israel

A dye tracer technique was utilized to measure the residence time distribution of the drops in a spray column, operating with a dispersed or a dense packing of drops, for a wide range of flow rates, in a 15 cm.in diameter, 150 to 160 cm. long column proper.

For dispersed packing of drops and for flow rates below the onset of coalescence, the flow of the drops was approximately plug flow, with a variance of the residence time distribution of 0.095. For flow rates above the onset of coalescence within the column, the variance increased sharply to 0.55 and decreased at higher flow rates.

For dense packing of drops the variance of the residence time distribution was in the range of 0.1 to 0.5. This variance is attributed to the effect of bypassing water and kerosene near the wall of the column. A mathematical model based on this effect showed reasonable fit with the experimental results. This model predicts an approach to plug flow of the drops for large diameter columns.

A spray column is the simplest device for countercurrent contacting of two liquid phases, and for either mass or heat transfer between the two phases. The overall performance of small spray columns has been widely reported in the literature. However, overall performance coefficients could not be correlated generally for different systems and columns, and scale up of spray columns, based on overall performance coefficients, was not successful. We have recently suggested (*9*) a mechanism for heat transfer in spray columns. The model assumed plug flow of the dispersed phase and showed good agreement with experimental temperature profiles, for dispersed packings of drops. It would be useful to know under what conditions the assumption of plug flow of drops holds, and what is the residence time distribution of the dispersed phase under other operating conditions, so that the scale up of spray columns can be modified accordingly.

Hazelbeck and Geankoplis (*3*) studied the axial dispersion of the continuous phase in a spray column for dispersed packings of drops. Mixon, et al. (*13*) studied the axial dispersion of both phases for a limited number of flow rates, with dispersed packings of drops and for one set of flow rates, with a dense packing of drops. In this work, the residence time distribution of the drops was measured for a wide range of flow rates of both phases, with dispersed and dense packings of drops. For dispersed packings of drops, the drops flow is nearly plug flow at flow rates below the onset of coalescence within the column. For dense packings of drops, the distribution of the velocities of drops is much wider. This is believed due to a wall effect, that induces bypassing of both phases near the wall and formation of a radial velocity profile in the core of the column.

EXPERIMENTAL PROCEDURE

A schematic drawing of the experimental apparatus is shown in Figure 1. The column was the 15 cm. in diameter, 160 cm. long (*8*), with some modifications. For operation with dense packings of drops the column was 150 cm. long. The top part of the column was conical, as shown by the dashed lines in Figure 1.

The water inlet in the first column was over the sides of the top of the column proper, which extended 10 cm. into the top cylindrical section. The water inlet in the second column was a 1.5 in. closed bottom tube, at the center and reaching down to the bottom of the top conical section. The water was dispersed through 3 mm. holes with a total area equal to the tube cross section area. The materials of construction of the column and the piping were aluminum, glass, and chrome plated brass.

The continuous phase was distilled water containing less than 2 ppm. of dissolved solids. The dispersed phase was kerosene. At 25°C. the measured physical properties of the kerosene were, density—0.78 g./cc., viscosity—0.90 centipoise, interfacial tension—45 dyne/cm. In order to minimize the effects of surface active agents, fresh water and fresh kerosene were used for each run and the column was often scoured and flushed. The range of flow rates for dispersed packings of drops was 0 to 40 liter/min. of water and 5 to 25 liter/min. of kerosene, and for dense packings of drops was 0 to 17

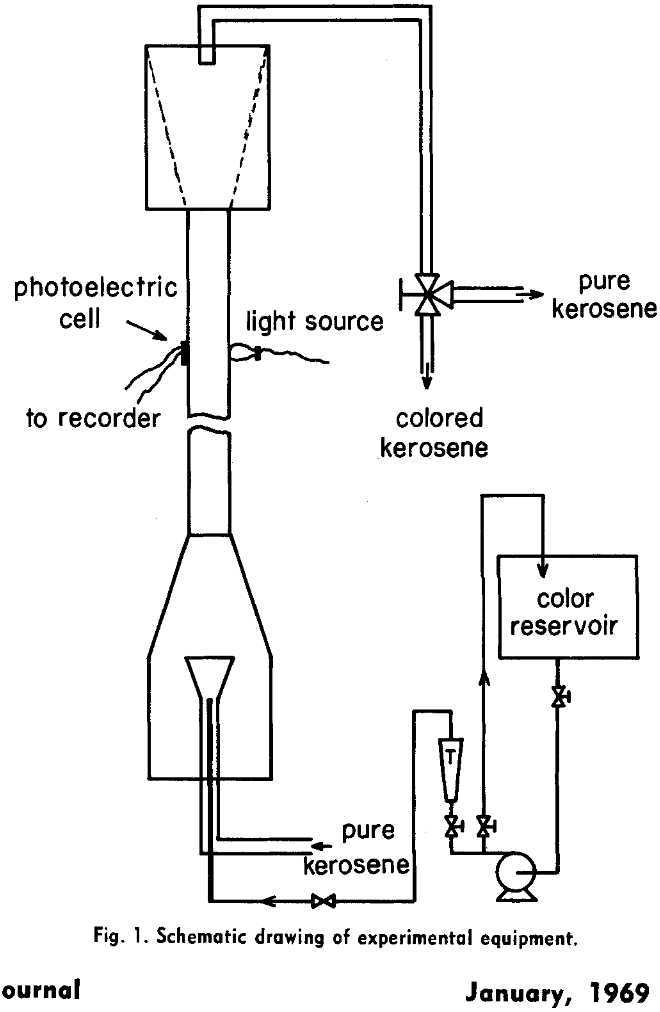

Fig. 1. Schematic drawing of experimental equipment.

liter/min. of water and 5 to 15 liter/min. of kerosene. The range of average drop diameters (except when coalescence within the column occurred) was 3.5 ± 0.5 mm. (*5*, *8*). The average holdup was measured separately for each set of flow rates for dense packings of drops.

The tracer was a solution in kerosene of a blue dye, insoluble in water. Measurements of the interfacial tension of the kerosene showed no effect of the addition of the blue dye. The blue dye, however, exerted some interfacial effect as the rate of coalescence of the kerosene drops decreased upon addition of the blue dye. A step change of concentration was used, since it was difficult to inject a very sharp pulse. The descending step was used in the analysis of the data, since it was sharper than the ascending step. The tracer solution was injected into the kerosene feed line, just below the mixing section under the distribution nozzles, which was filled with glass beads. The flow rate of the trace solution was about 1% of the bulk kerosene flow rate. For dense packings of drops the measuring point was near the top of the column, 145 cm. above the bottom of the column proper. For dispersed packings of drops, a lower position of 90 cm. above the bottom of the column proper was used, since at high flow rates the holdup at the top of the column decreased sharply (*8*).

The light source was a 150 w. lamp and the sensor was a photoelectric cell. The glass column was covered by dark paper and only two windows 2 × 1 cm. for the light source and sensor were used. Except at very low holdups the light passed through a number of kerosene drops on its way to the photoelectric cell. The output of the photoelectric cell was calibrated at each measuring point, for each set of flow rates and for either type of packing, by 5 to 10 different concentrations of the same dye in the bulk kerosene. This ensured that the calibration was made at the same holdup for each run. Even with this careful calibration, the measured concentrations deviated from the actual values, since for the calibration runs all the kerosene drops were dyed, whereas in the experimental runs a changing fraction of the kerosene drops was colorless. However, this method is much better than measurements of the concentration at the kerosene outlet. Early experiments showed that the effects of mixing in the coalescence zone and of flow above the coalescence zone, obscured most of the effects of the residence time distribution within the column. The large scatter of the data for dense packings of drops is due to the fact that the flow patterns of the drops were not symmetrical and the measurements were conducted on a fixed 2 × 1 sq. cm. radial section of the column.

TREATMENT OF DATA

The residence time distribution in a flow system is usually analyzed by the diffusion model (*3, 10, 13, 14*) and the results are correlated as Peclet (or Bodenstein) numbers against Reynolds numbers. The diffusion model is a useful approximation for the purpose of comparison and correlation of data. However, the values of the Peclet number also appear to be a function of particle diameter (*11*), of the type of packing and shape of voids (*4*), of the location of the sensor (*4*), and of the Schmidt or Prandtl numbers (*12*). Mixon, et al. (*13*) points out that the scatter in their data can be attributed to the inadequacies of the diffusion model in representing the flow pattern and mixing behavior inside the spray column. In the present work the variance of the residence time distribution was used for the analysis of the experimental data and Peclet numbers were calculated only for the purpose of comparison with other works.

The experimental data were recorded as concentration/time curves. These curves were initially invariable, followed by a sharp drop and then by a slow drop of concentration with a long tail. For dense packings of drops, the tail was long and the times at the end of the invariable period (t_1) and the end of the tail (t_2) were also regarded as data. The time at the end of the tail was taken at 1% of the steady state concentration. This time corresponded to the presence of the last few colored drops in the column.

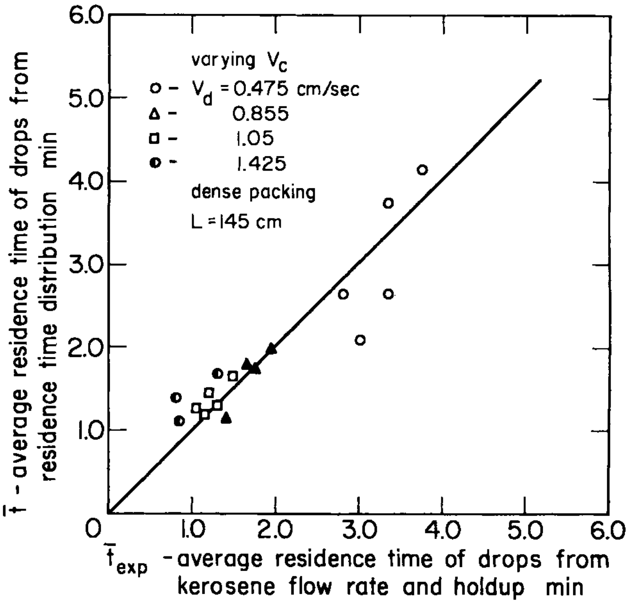

Fig. 2. Average residence time from drop residence time distribution curves and from kerosene flow rate and holdup.

The experimental concentration/time curves were differentiated to give the residence time distribution of the drops. The average residence time of the drops ($\bar{t}$) and the variance (σ^2) were calculated by the conventional methods from the residence time distribution of the drops (*10*). The average residence time could also be calculated from the kerosene flow rate and the average holdup of drops in the measured volume

$$\bar{t}_{\text{exp}} = \frac{H}{V_d} L \tag{1}$$

For a closed system $\bar{t}_{\text{exp}} = \bar{t}$, while for an open system with backmixing $\bar{t}_{\text{exp}} \neq \bar{t}$ (*10*).

For the runs with a dense packing of drops, the measuring point was close to the top of the packing and the system can be considered as a closed system. The values of $\bar{t}$ and $\bar{t}_{\text{exp}}$ are compared in Figure 2 for dense packings of drops. There is some scatter of the data, but the general trend confirms that $\bar{t} = \bar{t}_{\text{exp}}$. The values of $\bar{t}_{\text{exp}}$ were used for the correlations, since the accuracy of the values of $\bar{t}_{\text{exp}}$ is higher, as unlike the residence time distribution data, they were not affected by the asymmetrical flow patterns of the drops.

For the runs with dispersed packings of drops, the experimental results are plotted in Figure 3 in the form of the variance of the residence time distribution against dimensionless holdup. The holdup for the run was related to the holdup at the same kerosene flow rate, (and a higher water flow rate) for which coalescence starts within the column (*8*). This method was used to emphasize the role of coalescence on the residence time distribution of the drops. The dimensionless holdup is related to the average velocity of the drops since

$$\frac{H}{H_{\text{coal}}} = \frac{V_d}{H_{\text{coal}}} \times \frac{H}{V_d} = \frac{\overline{V}_{\text{coal}}}{\overline{V}} \tag{2}$$

For dense packings of drops the experimental results are plotted in Figures 4 to 6 in the form of the velocity of the fastest drops, the velocity of the slowest drops and the variance of the residence time distribution of the drops against the average velocity of the drops. The values of

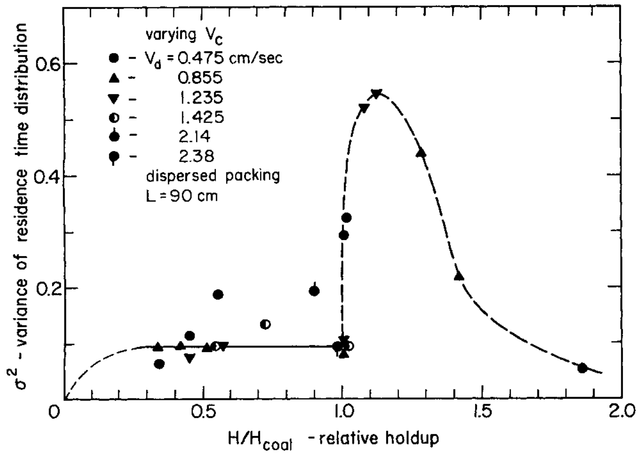

Fig. 3. Variance of residence time distribution for dispersed packings of drops as function of relative holdup.

time and velocity are related by:

$$\overline{V} = \frac{L}{t_{\text{exp}}},\; V_1 = \frac{L}{t_1},\; V_2 = \frac{L}{t_2},\; \overline{V_p} = \frac{L}{t_p} \qquad (3)$$

However, values of t are associated with a particular column length and the values of V are free from that restriction.

EFFECT OF DISTRIBUTION OF DROP SIZE

Angelo and Lightfoot (*1*) measured the residence time distribution of drops in a one plate sieve column, with an effective height of 55 cm., at low holdups. They attributed the residence time distribution of the drops, in addition to the effect of bypassing flows, to the difference of free rise velocities due to the distribution of drop size. In our work, for both dispersed (*8*) and dense (*5*) packings of drops, a narrow distribution of drop size with a variance of 0.05 was found, over most of the range of the operating variables (except when coalescence within the column took place). The drops were moving at velocities lower than their free rise velocities, except at very low holdups. The free rise velocity of drops is a function of drop size. However, for holdups of over 0.10, the flow field of each drop is affected by the fields of adjacent drops. A large drop, moving at a high velocity, can carry in its wake a smaller drop. The combined velocity of the two drops will be smaller than the free rise velocity of the larger drop, and greater than the free rise velocity of the smaller drop. Therefore, except at very low holdups, the distribution of drop sizes should have only an insignificant effect on the velocity distribution of the drops.

DISPERSED PACKINGS OF DROPS

Visual observations of the flow patterns, for dispersed packings of drops, at low holdups, showed a spiral motion of drops in the upward direction only. This was also noted by other observers (*1*). At high holdups, some drops were retarded at the wall of the column and this retardation increased with increased flow rates. At the flow rates for which the bottom of the packing of drops was within the bottom conical section, oscillations of the denser bed of drops in the conical bottom section caused drops to be captured within the conical bottom section and to move back and forth. Coalescence of drops and severe backmixing of drops were also noted in this flow region.

The behavior of the variance of the residence time distribution of the drops (Figure 3) is in accord with the visual observations. The variance is independent of holdup (and flow rates), up to the onset of coalescence, with a value of 0.095, which can be regarded as practically plug flow. The variance of 0.095 is probably due to a radial velocity profile induced by the walls. Kintner (*6*) found a parabolic velocity profile of the drops in spray columns with dispersed packings of drops. The lower velocity of the drops at the wall is due to bypassing of water at higher velocities at the wall, than away from the wall. The amount of bypassing as calculated from the temperature profile of the water (*7*) was in the range of 0 to 10% of the water throughput, with most of the data falling between 2 and 5% of the water throughput.

For flow rates just above the onset of coalescence, the variance increases sharply to 0.55 with considerable divergence from plug flow. In this range of flow rates the average drop size increases sharply within the column from 3.3-3.5 to 5-7 mm. and the variance of the drop size distribution increases (*7*). The sharp increase of the variance of the residence time distribution is due to a combination of irregular flow patterns and backmixing, to oscillations of the denser packing of drops in the bottom conical section, and to the increasing variance of drop size.

At higher flow rates ($H/H_{\text{coal}} > 1.2$) channels of coalesced kerosene are formed in the lower part of the column (*7*) and break up higher up the column. The flow pattern is dominated by the movement of the kerosene channels and the variance of the residence time distribution decreases.

It was noted earlier (*8*) that flooding in a spray column can be defined as the flow rates of the two phases, at the maximum value of specific area of the drops in the column. This definition corresponds to the point of start of coalescence within the column and also to an operating curve with a minimum point at the bottom of the column proper (*8*). It now appears that this definition of flooding also corresponds to the sharp increase of the variance of the residence time distribution of the drops.

DENSE PACKINGS OF DROPS

Visual observations of the flow patterns of dense packings of drops were more revealing when pulses of a dyed kerosene tracer were injected into the column and facilitated the observation of single drops near and away from the walls. Bypassing of narrow, irregular and asymmetric, swarms of kerosene drops adjacent to the walls and moving at higher velocities than the drops in the core of the column was observed. Bypassing of asymmetric channels of water down the column also took place at the wall

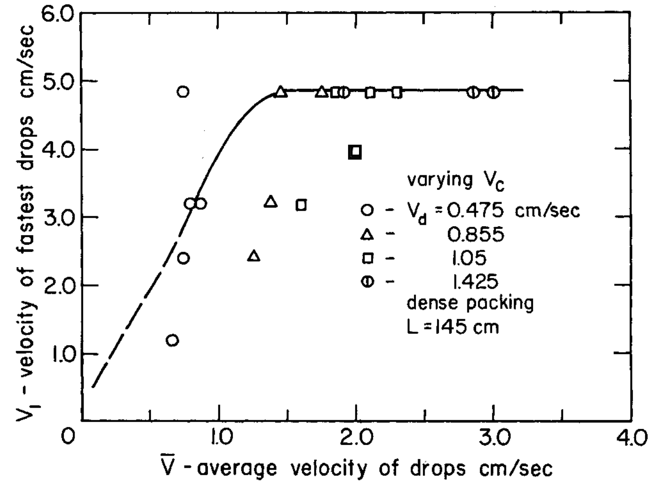

Fig. 4. Velocity of the fastest drops as function of average velocity, for dense packings of drops.

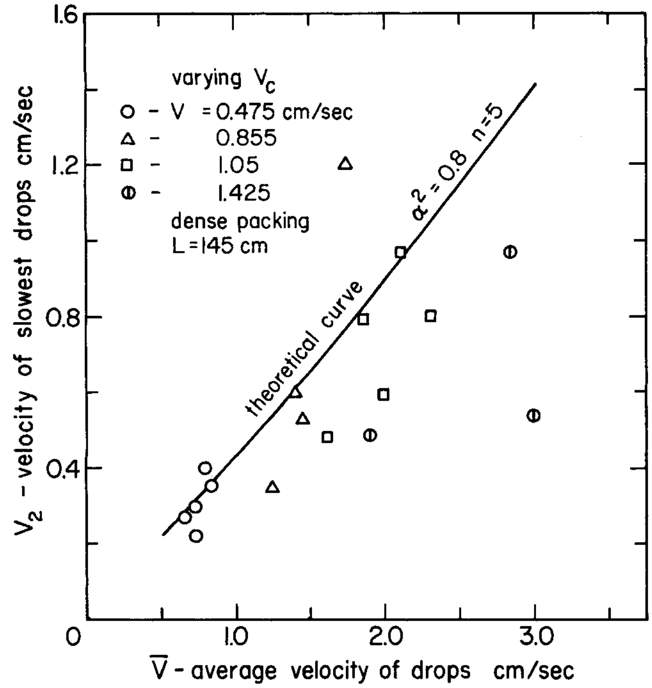

Fig. 5. Velocity of the slowest drops as function of average velocity, for dense packings of drops.

(Figure 7*a*). Drops adjacent to the bypassing water were retarded and the slower drops in that region produced the long tail in the concentration/time curves. The velocity of the fast swarms of drops appeared constant for a wide range of flow rates of the two phases. This is confirmed in Figure 4 for the range of $3.0 \geq \bar V \geq 1.5$ cm./sec. This velocity decreases considerably, however, with decreased velocity of drops for low flow rates of kerosene, for the range of $\bar V \leq 1.5$ cm./sec. The velocity of the slowest drops in the column is roughly proportional to the average velocity of the drops (Figure 5). The variance of the residence time distribution of the drops showed a slightly decreasing trend with increased average velocity of the drops (Figure 6). The range of the variance was from 0.1 to 0.5, with most of the data falling in the range of 0.2 to 0.4, much higher values than those obtained for the operating range of dispersed packings of drops. The drops in a dense packing of drops are spaced much closer than in a dispersed packing of drops and the retardation of velocity induced near the walls is transferred radially more fully.

The visual observations and the concentration/time curves indicate that the velocity distribution of the drops is induced by two factors, the retardation of drops by the bypassing water with the establishment of a radial velocity profile and the flow of many fast irregular swarms of drops near the wall. Most of the vicinity of the wall is occupied by the bypassing water flowing down and part of this volume is occupied by the bypassing kerosene drops flowing up the column (Figure 7*a*). From these observations a simplified model of the residence time distribution is proposed.

THEORETICAL MODEL FOR DENSE PACKINGS OF DROPS

An idealized form of the bypassing streams is shown in Figure 7*b*. An annular channel of kerosene drops of thickness $(1 - \alpha)R$ is assumed to flow in plug flow up the column. An annular channel of water of negligible thickness flowing down the column lies adjacent to and inside the annular channel of the kerosene drops. In the central core of the column the kerosene drops flow with a radial velocity profile. The fast downward flow of bypassing water retards the drops adjacent to it and establishes the velocity profile of the drops. The velocity profile in the core region, for $\alpha = \left(\frac{r}{R}\right)_{\max} < 1$, is assumed to have a flattened parabolic form of:

$$V_r = \frac{\bar V_p}{a}\left[1 - \left(\frac{r}{R}\right)^n\right] \tag{4}$$

This is a one parameter equation. It will be shown later that a is a function of n only.

The local residence time of drops is:

$$t_r = \frac{L}{V_r} = \frac{aL}{\bar V_p}\,\frac{1}{1-\left(\frac{r}{R}\right)^n} = \frac{a\bar t_p}{1-\left(\frac{r}{R}\right)^n}$$

$$= a\,\bar t_p\left[1 + \left(\frac{r}{R}\right)^n + \left(\frac{r}{R}\right)^{2n} + \ldots\right] \tag{5}$$

The relation between a and n can be calculated by the definition of the average residence time of the drops in the core region and Equation (5)

$$\bar t_p = \frac{\int_o^{\alpha R} 2\Pi r t_r dr}{\int_o^{\alpha R} 2\Pi r dr}$$

$$= \frac{a\,\bar t_p}{\alpha^2/2}\left[\frac{\alpha^2}{2} + \frac{\alpha^{n+2}}{n+2} + \frac{\alpha^{2n+2}}{2n+2} + \ldots\right] \tag{6}$$

and therefore

$$a = \frac{1}{1 + \frac{2}{n+2}\alpha^n + \frac{2}{2n+2}\alpha^{2n} + \ldots} \tag{7}$$

For a fixed amount of bypassing (constant α) a is a function of n only. For a large column diameter the velocity profile flattens, $n \to \infty$, $a \to 1$, and from Equation (4) for $r < \alpha R$, $V_r = \bar V_p$. Plug flow of drops in the core can therefore be expected for large diameter columns.

The residence time of the slowest drops can be obtained from Equation (5) at $\frac{r}{R} = \alpha$

$$t_2 = \frac{a\,\bar t_p}{1-\alpha^n} \tag{8}$$

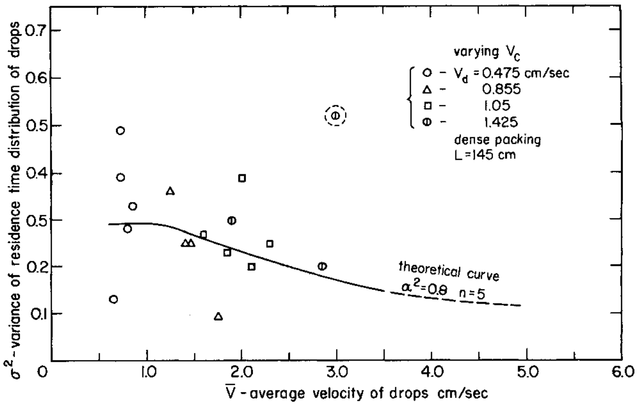

Fig. 6. Variance of residence time distribution of drops as function of average velocity, for dense packings of drops.

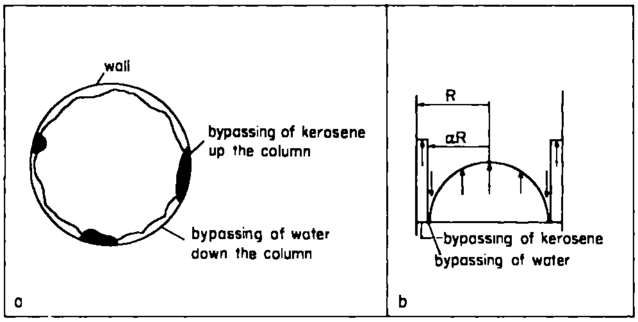

Fig. 7. Patterns of bypassing kerosene and water. a. observed. b. simplified model.

The variance of the residence time distribution of the drops inside the core can be calculated from the second moment of the residence time distribution (*10*):

$$\sigma_p^2 = \frac{\int_0^{\alpha R} 2\Pi r t_r^2 dr}{\bar{t}_p^2 \int_0^{\alpha R} 2\Pi r dr} - 1$$

$$= \frac{2\alpha^2}{n(1-\alpha^n)} + \alpha\left(1 - \frac{2}{n}\right) - 1 \quad (9)$$

Therefore, for constant α and n, σ_p^2 is also constant.

For comparison with experimental data, the average residence time of the drops in the whole cross section of the column and the total variance of the residence time distribution of the drops are desired.

The average residence time in the whole cross section is the average residence time distributions of the drops in the core and in the annulus:

$$\bar{t} = \alpha^2 \bar{t}_p + (1-\alpha^2)\, t_1 \quad (10)$$

and hence,

$$\bar{t}_p = \frac{1}{\alpha^2}\, [\bar{t} - (1-\alpha^2)\, t_1] \quad (11)$$

The residence time of the slowest drops can be calculated from Equations (8) and (11):

$$t_2 = \frac{\alpha}{\alpha^2(1-\alpha^n)}\, [\bar{t} - (1-\alpha^2)\, t_1] \quad (12)$$

For the calculation of the total variance it is first necessary to relate the variance in the core to the average residence time in the total cross section by:

$$\sigma_{pt}^2 = \frac{\int_0^{\alpha R} (t_r - \bar{t})^2 r\, dr}{\bar{t}^2 \int_0^{R} r dr}$$

$$= \left[(\sigma_p^2 + 1)\left(\frac{\bar{t}_p}{\bar{t}}\right)^2 - 2\frac{\bar{t}_p}{\bar{t}} + 1 \right] \alpha^2 \quad (13)$$

The variance of the residence time distribution of the bypassing drops is:

$$\sigma_{bp}^2 = \frac{(\bar{t} - t_1)^2}{\bar{t}^2}\, \frac{(\Pi R^2 - \Pi\alpha^2 R^2)}{\Pi R^2} = \frac{(1-\alpha^2)(\bar{t} - t_1)^2}{\bar{t}^2} \quad (14)$$

By addition of these two variances and the use of Equations (3) and (11) the total variance of the residence time distribution of the drops is obtained

$$\sigma^2 = \left[\frac{1}{\alpha^2}(\sigma_p^2 + 1) - 1 \right]$$

$$+ 2\left(1 - \frac{1}{\alpha^2}\right)(\sigma_p^2 + 1)\frac{\bar{V}}{V_1}$$

$$+ \left[(1-\alpha^2) + (\sigma_p^2 + 1)\left(\frac{1}{\alpha} - \alpha\right)^2 \right]\left(\frac{\bar{V}}{V_1}\right)^2 \quad (15)$$

Equations (3), (7), (9), (12), and (15) make possible the calculation of t_2 and σ^2 as function of α, n, $\bar{t}$, and t_1 (or $\bar{V}$ and V_1).

The fraction of column cross section in which bypassing of drops takes place was calculated by a method similar to the one suggested by Levenspiel (*10*), and used by Angelo and Lightfoot. This fraction varied from 0.10 to 0.2 (α^2 — 0.8–0.9). The fractional bypassing decreased with decreasing holdup. Since the range of values of α^2 is narrow, it is convenient to use a single value of α^2 for the whole range instead of using a different value of α^2 for each run. Since most runs were at high holdups, a value of $\alpha^2 = 0.8$ was used. Values of V_1 as function of $\bar{V}$ were taken from the smoothed data of Figure 4. Several values of n were used for each case. The values of α^2 decreased with increasing n, as expected from the theoretical model. For $\alpha^2 = 0.8$, $n = 5$ was used. For these values $\sigma_p^2 = 0.135$ and

$$V_2 = \frac{\bar{V}}{2.45 - 0.5\left(\frac{\bar{V}}{V_1}\right)} \quad (16)$$

$$\sigma^2 = 0.42 - 0.565\left(\frac{\bar{V}}{V_1}\right) + 0.256\left(\frac{\bar{V}}{V_1}\right)^2 \quad (17)$$

The limiting conditions for $\bar{V} = 0$ and $\bar{V} = \infty$ have no physical counterparts. The theoretical equations show reasonable agreement with the experimental data (Figures 5 and 6). The agreement could have been better if point values of α were used and if n were allowed to vary with varying holdup, but the scatter of the data does not justify the additional work involved. For decreasing holdups the value of n increases and the radial velocity profile should flatten. Accurate values of n may be obtained when radial velocity profiles can be determined experimentally.

SCALE UP

Spray columns operating with dispersed packings of drops at flow rates below the onset of coalescence within the column can be scaled up by the assumption of plug flow of the drops (9). The radial velocity profile is induced by the effect of bypassing of water near the wall, and this effect is negligible for large diameter columns.

Spray columns operating with dense packings of drops can be scaled up by the following reasoning: The thickness of the bypassing annulus (b) does not vary much with increased column diameter. The fractional cross section area for bypassing is therefore

$$1 - \alpha^2 = \frac{\Pi D\, b}{\frac{\Pi D^2}{4}} = \frac{4\, b}{D} \quad (18)$$

and decreases as column diameter is increased. If D_1 is the diameter of the experimental column and D_2 is the diameter of the larger column, the value of α_2 can be calculated from α_1 by:

$$\frac{1 - \alpha_2^2}{1 - \alpha_1^2} = \frac{D_1}{D_2} \quad (19)$$

The retardation of the velocity of the drops at the center of the column decreases with increase of column diameter. As an approximation it is suggested to take $n \alpha D$ and therefore:

$$\frac{n_2}{n_1} = \frac{D_2}{D_1} \qquad (20)$$

The values of V_1 in the constant velocity region should not vary with column diameter for the same average size of drops.

Equations (19) and (20) can be used for an approximate scale up of the data from the 6 in. column. For large diameter columns it was shown in the theoretical model that the flow of drops should be essentially plug flow.

DISCUSSION

The analysis of the experimental data is based on the assumption that the velocity distribution of drops, in a nonflooded column, is caused by the bypassing flow at the wall of drops and continuous phase. Angelo and Lightfoot (*1*) also suggest that bypassing of both phases was the most serious effect on the flow pattern, in their one plate sieve column.

The simplified model suggested in this work for the velocity distribution of the drops, for dense packing of drops, predicts an approach to plug flow of the drops in columns of large diameter and this is the main useful application of the theoretical model. The effect of bypassing and of the radial velocity distribution is to reduce the overall performance of a spray column. Therefore, increasing the diameter of laboratory size columns, operating with dense packings of drops, should improve the overall performance of the spray column. No such data is available in the literature for extraction spray columns and only limited such data are available for heat transfer in spray columns. Greskovitch (*2*) studied heat transfer in spray columns that included two columns 10 ft. long, 4 and 6 in. in diameter. Comparison of his *HTU* data for the same flow conditions with dense packings of drops shows a 40% reduction of the values of *HTU* as the column diameter was increased from 4 to 6 in. This confirms the results of the present work and also serves to illustrate the danger of using overall performance coefficients for scale up without taking into account the effects of the flow patterns in the column.

In most studies of residence time distribution, Peclet numbers are calculated from the residence time distributions and are correlated with flow conditions. For the purpose of comparison of the results of this work with other works, values of Peclet numbers were calculated from the variance of the residence time distribution by the equation given by Levenspiel (*10*) for closed vessels

$$\sigma^2 = 2\left\{\frac{1}{N_{Pe}} - \frac{1}{N_{Pe}^2}\left[1 - \exp\left(-N_{Pe}\right)\right]\right\} \qquad (21)$$

The range of most Peclet numbers calculated from the experimental data was 4 to 8.5 and averaged around 6. No effects of flow conditions were noted. Mixon, et al. (*13*) obtained for dense packings of drops, at one set of flow rates, a Peclet number of 0.13 (at $\bar{t} = 0.44$ min.) for a 6 in. column 3 ft. long and a Peclet number of 2.1 (at $\bar{t} = 0.36$ min.) for a 3 in. column 3 ft. long. These values indicate a much greater dispersion of velocities of drops than that obtained in the present work. However, the flow rates, holdups, and drop sizes were not specified by Mixon, et al., and direct comparison with his results is not possible in view of the large scatter usually found in this type of data. The effect of column diameter in their work is also obscured by the different average residence times of the drops in both columns.

CONCLUSIONS

For dispersed packings of drops:

1. For flow rates below the onset of coalescence within the column, the variance of the residence time distribution of the drops is 0.095, indicating a practically plug flow of drops.
2. With the onset of coalescence within the column, the variance rises sharply to a maximum value of 0.55. For higher flow rates and increased coalescence within the columns, channels of kerosene are formed in the column and the variance decreases.

For dense packings of drops:

1. The experimental variances of the residence time distribution of the drops range between 0.1 and 0.5. The general trend is an increase of the variance with decreasing average velocity of the drops.
2. The variance of the residence time distribution of the drops is caused by the bypassing of fast swarms of drops near the column wall and by the radial velocity profile of the drops induced by bypassing water near the wall.
3. The variance of the residence time distribution of the drops should decrease with increasing column diameter and the drops should flow in essentially plug flow for large diameter columns.

ACKNOWLEDGMENT

This work was supported by the Israel National Council for Research and Development.

NOTATION

a = coefficient in Equation (4)
b = thickness of bypassing annulus, cm.
D = diameter of column, cm.
H = average holdup
H_{coal} = average holdup at a particular flow rate of the dispersed phase at the water flow rate for onset of coalescence
L = height of measuring point above bottom of column proper, cm.
n = exponent in Equation (4)
N_{Pe} = Peclet number
r = local radius in the column, cm.
R = radius of column, cm.
$\bar{t}$ = average residence time of drops from residence time distribution, min. or sec.
$\bar{t}_{exp}$ = average residence time of drops from throughput and holdup, min. or sec.
$\bar{t}_p$ = average residence time of drops in the core of the column, min. or sec.
t_r = local residence time of drops at radius r, min. or sec.
t_1 = residence time of fastest drops, min. or sec.
t_2 = residence time of slowest drops, min. or sec.
$\bar{V}$ = V_d/H average velocity of drops in the column, cm./sec.
$\bar{V}_{coal}$ = average velocity of drops at H_{coal} for a particular flow rate of the dispersed phase, cm./sec.
V_c = superficial velocity of the continuous phase, cm./sec.
V_d = superficial velocity of the dispersed phase, cm./sec.
$\bar{V}_p$ = average velocity of drops in the core, cm./sec.
V_r = local velocity of drops at radius r, cm./sec.
V_1 = velocity of fastest drops, cm./sec.

V_2 = velocity of slowest drops, cm./sec.

Greek Letters

α = ratio of core radius to column radius
σ^2 = variance of residence time distribution of drops in the whole column
σ_p^2 = variance of residence time distribution of drops in the core
σ_{pt}^2 = variance of residence time distribution of drops in the core related to the average residence time of drops in the whole cross section area
σ_{bp}^2 = variance of residence time distribution of by-passing drops

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Manuscript received August 18, 1967; revision received December 14, 1967; paper accepted January 10, 1968.

The Synthesis of System Designs

II. Heuristic Structuring

A. H. MASSO and D. F. RUDD

The University of Wisconsin, Madison, Wisconsin

The use of heuristic structuring strategies in the development of computer programs for the synthesis of process designs is examined. By the employment of selection weights which are adjusted as experience is gained from past successes and failures, the computer is able to learn the sequence of structuring decisions which leads toward the optimal process design. The computer can develop competence in the synthesis of systems in a limited area of technology.

A basic problem in engineering is that of synthesizing from available components a system which best performs a processing task. The trial and error synthesis of all possible system structures may be ruled out as a plausible design method; for, in all but the simplest of design problems, the number of ways in which the system might be structured is overwhelmingly large. In a previous report (*1*) the principle of problem decomposition was examined and shown to hold promise as a practical means of system synthesis. In this report, we examine a different approach and relate experiences in the development of a program which enables the digital computer to gain competence in the synthesis of heat exchanger networks. Although this work is still in a primitive stage, it holds promise of increasing the usefulness of the comupter in process design.

A dilemma is encountered in the synthesis component by component of a performing process. One cannot know how the addition of a component to the partially synthesized system will affect the system performance because the complete system does not yet exist. Thus, there can be no strictly valid criterion for selecting one component over another, or one structural arrangement over another while in the midst of system synthesis. The lack of a valid criterion leads directly to the enormous combinatorial problem of synthesizing all possible structures. Selection rules which favor the use of a given piece of equipment in certain phases of system synthesis evolve from experience and are thought to be part of the empirical skill of successful process designers. These rules may be wrong on occasion and will lead to nonoptimal systems, but the experienced designer requires only that the rules lead to efficient designs frequently enough to warrant their use.

Overwhelming problems which defy analysis arise in areas other than engineering, such as in the playing of chess or the proving of theorems in mathematics. The mental processes of the experienced chess player or the experienced mathematician seem to involve the use of rules of thumb that circumvent problems in analysis which are beyond detailed solution. These rules are called *heuristics*, and are described as methods of problem solving which are useful empirically but are unproved, or incapable of being proved.

This is a report on experiences in the development of heuristic structuring programs which enable the computer to learn to synthesize system structures. The general procedure is as follows. A basis for incorporating particular processing steps in the system structure is obtained from various design criteria with which the computer is supplied. Synthesis of the required process, then, results from the selection of a sequence of such steps. Hence, the problem is that of enabling the computer to teach itself to select the optimal sequence of design decisions. This is done by assigning selection weights to the criteria, and adjusting these weights to assimilate the experience gained through previous synthesis trials. The design criteria plus the means of manipulating the selection weights constitute the heuristic structuring rules.

The concepts and nomenclature used here are consistent with part I of these studies (*1*). In the section