Mixing Effects in a Spray-Column Heat Exchanger

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Temperature profiles were measured in a spray-column heat exchanger 7.5 cm. in diameter and 167 cm. long between the inlets of warm kerosene and cold water. The temperature jump, at the inlet of the continuous phase, is a measure of the amount of mixing in the column and is a function of holdup and ratio of flow rates of the two phases. At holdup the temperature jump had a minimum value of 0.24.
A physical model for heat transfer in a spray column based on hydrodynamic principles is proposed. Heat is transferred from drop to wake downstream of drop. Wakes are shed and mixed with the bulk water flow. New material enters the wake and is spilled out at higher temperatures.
The physical model is applied to explain the data on temperature jumps in spray-column heat exchangers and the data on concentration jumps in spray-column extractors.

Countercurrent heat transfer between two immiscible liquids in a spray column has been studied extensively (*1, 2, 14, 25, 28, 32, 33, 39, 40*). The spray-column operation is characterized by longitudinal mixing in the continuous phase, but there is practically no mixing in the dispersed phase (*7, 18*).

Several mathematical methods were developed recently to calculate extraction efficiencies in spray columns (*10, 29, 30, 35, 38*). However, these methods require experimental values of longitudinal dispersion coefficients (E_l). Brutvan (*4*) and Hazelbeck and Geankoplis (*20*) measured E_l of the continuous phase in spray columns. Brutvan used glass beads and water and measured E_l only in the center portion of the column. Hazelbeck and Geankoplis used methyl isobutyl ketone and water and operated their column at holdups under 0.05. The two investigations were in different ranges of Reynolds numbers, and the correlation of Hazelbeck and Geankoplis shows that their values of Peclet numbers were approximately 2.5 times those of Brutvan.

Considerable work has been done on longitudinal dispersion in packed beds. An excellent summary of this work by Hiby (*23*) shows that the Peclet numbers obtained by different investigators with the same packings vary by as much as an order of magnitude under the same flow conditions.

Two investigations of longitudinal dispersion coefficients in fluidized beds (*6, 26*) show also considerable variance in results.

The spray column is characterized by a sharp drop in the driving force at the inlet of the continuous phase. A concentration discontinuity, or jump, was noted in studies of extraction spray columns (*7, 16* to *18, 27, 37*), and a temperature jump was noted in a spray-column heat exchanger (*32*). These phenomena were attributed to longitudinal dispersion (*20, 29, 35, 38*) or to recirculation of the continuous phase (*7, 15, 18, 27, 31, 32, 37*). Part of the concentration jump was attributed to coalescence of drops at the upper interface (*7, 18*).

This work attempts to correlate the temperature jump of the water with flow variables at the inlet and to propose a physical model that is consistent with the behavior of spray columns.

EXPERIMENTAL

Water was used as the continuous phase and kerosene as the dispersed phase.

The spray column, based on one of Elgin's (*3*), had an internal diameter of 7.5 cm., the length of the column proper was 150 cm., and the distance between the two inlets was 167 cm. The central part of the column was a glass dewar 54 cm. long, and the rest of the column was made of brass and insulated with glass wool. The rate of heat loss was less than 1% of the heat transfer rate.

The kerosene distribution plate was of brass 2.1 mm. thick and 7.0 cm. in diameter, with thirty 1.5-mm. orifices arranged in concentric circles.

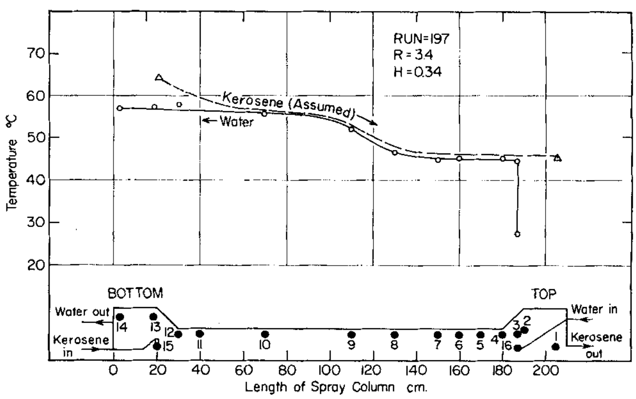

Fig. 1. Typical temperature profile and location of thermocouples.

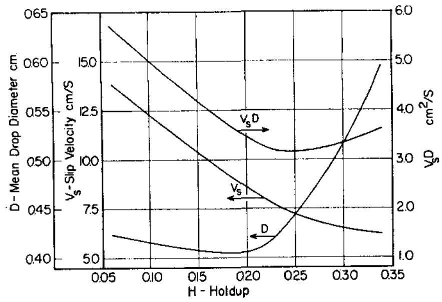

Fig. 2. Mean drop diameter, slip velocity, and product of both as function of holdup.

MEASUREMENTS

The temperature was measured by sixteen 30-gauge copper-constantan thermocouples packed in ⅜-in. copper tubing that ran through the length of the column. Figure 1 is a scale drawing of half the spray column, showing the locations of the thermocouples and a typical temperature profile. The temperature was measured to within 0.05°C.

Holdup and mean drop diameters as functions of the flow rates were measured at room temperature. Details of these measurements are given elsewhere (28). Some pertinent results of these measurements were replotted in Figure 2 by use of mean drop diameters, slip velocity, and the product of the mean drop diameter and the slip velocity as functions of the holdup of the kerosene drops in the column.

TEMPERATURE PROFILES

The water inlet temperature was 25°C., and the kerosene inlet temperatures were in the range of 35° to 70°C. The ratio of flow rates of kerosene to water was 0.7 to 3.4. The holdup of kerosene drops in the column was 0.05 to 0.38.

The temperature profile in Figure 1, which is typical of all temperature profiles obtained, shows a slow rate of temperature change of the water at the bottom of the column, a fast temperature change at the middle of the column, a slower temperature change higher the column, and a sharp jump of temperature at the water inlet. Similar sigmoidal profiles were presented by Pierce et al. (32) for temperature and by Cavers and Ewanchyna (7, Figure 8) for concentration.

Figure 3 shows the effect of holdup and of the ratio of flow rates on the temperature profiles. Dimensionless temperature profiles (θ) were used, where

$$\theta = \frac{t_w - t_{wi}}{t_{wo} - t_{wi}} \qquad (1)$$

$\theta = 0$ at the water inlet (0 length in Figure 3 and 20 cm. in Figure 1), and $\theta = 1$ at the water outlet (1.0 length in Figure 3 and 187 cm. in Figure 1).

At lower holdups, the temperature of the water was nearly constant in the lower part of the column. At holdups above 0.24 the lower part of the column was more effective in transferring heat than at lower holdups, and the water temperature started to change at a lower point in the column. Experiments with varying temperatures of the kerosene at the kerosene inlet resulted in curves similar to Figure 3.

DISCUSSION

Temperature-Jump Ratio

Figure 4 shows the temperature jump at the inlet of the continuous phase, as a function of the holdup ratio of flow rates and temperature, in a dimensionless form θ_a, where

$$\theta_a = \frac{t_{wa} - t_{wi}}{t_{wo} - t_{wi}} \qquad (2)$$

The jump ratio (θ_a) was defined earlier for concentration by Miyauchi and Vermeulen (29). For a perfectly mixed flow $\theta_a = 1$, and for true countercurrent flow $\theta_a = 0$. Therefore the values of the jump ratio are a measure of the degree of mixing in the spray column. This can be visualized in the following way. The spray column may be considered as a series of perfectly mixed mixing vessels. (It will be shown later that this is also the physical behavior of the spray column.) For a very large number of mixers, true countercurrent operation is approximated, and $\theta_a = 0$. As the number of mixers becomes smaller, the size of each mixer increases and θ_a increases. When the number of mixers decreases to one, the whole column behaves as a single mixer and $\theta_a = 1$. Another characteristic of the jump ratio is that it is defined by the temperatures of only one phase. Jump ratios as high as 0.65 were obtained for high ratios of flow rates for both low and high holdups.

Figure 4 shows no significant effect of kerosene inlet temperature in the range of 35° to 65°C. Since the jump ratio also indicates the limiting temperatures that can be reached by the kerosene at the top of the column, this means that the external temperature difference between the two streams at the top of the column increases as the inlet temperature of the kerosene is increased.

The jump-ratio curves show a minimum at holdup of 0.24. This is also the holdup for the minimum of the product of mean drop diameter and slip velocity (Figure 2).

Extrapolation of the converging tendency of the two curves in Figure 4 at low holdup suggests that at zero holdup the jump ratio is independent of the ratio of flow rates. At increasing holdups, the jump ratio increases with increased ratio of flow rates. Above holdup of 0.24 the data of Figure 4 show pairs of jump ratios that bear the same ratios to each other as do the corresponding flow-

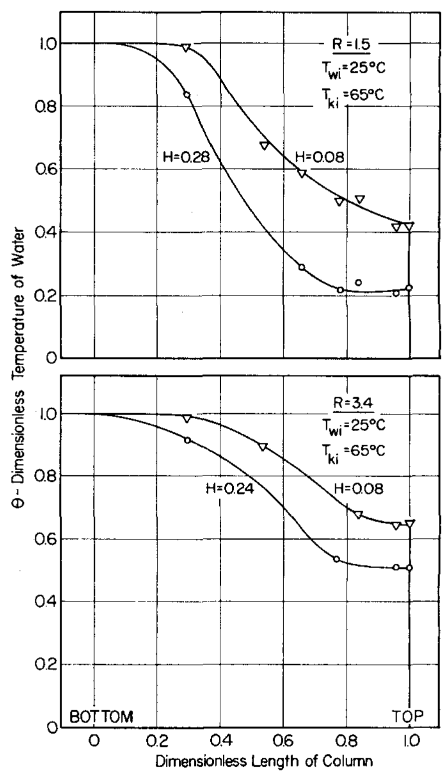

Fig. 3. Dimensionless temperature profiles of the continuous phase.

rate ratios. Thus jump ratio appears to be directly proportional to ratio of flow rates at higher holdups.

This proportionality holds for a wide range of ratios of flow rates at the minimum of the jump-ratio curves. This is shown in Figure 5, where the minimum temperature-jump ratio is plotted against the ratio of flow rates. Most of the series of temperature profiles, represented by one point each in this curve, were made with the orifices in the dispersion plate partly blocked by scale. Visual observations of the drop sizes indicated that the drop diameters were smaller in these experiments than in the experiments with clear, unblocked orifices. The holdup at the minimum jump ratio for each ratio of flow rates was in the range of 0.21 to 0.24 for the partly blocked orifices.

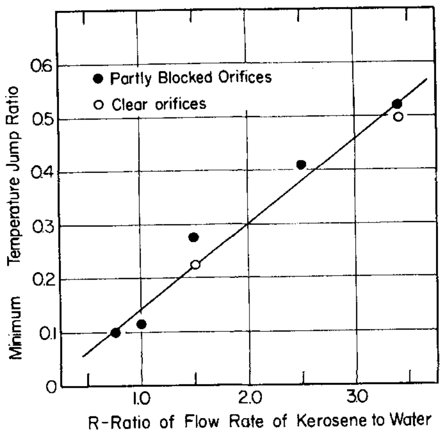

Fig. 5. Minimum-jump ratios as functions of the ratio of flow rates.

HYDRODYNAMIC BEHAVIOR OF DROPS

The hydrodynamic behavior of drops is reviewed here in order to provide the background for the proposed physical model of heat transfer in a spray column.

Garner et al. (*12*) reviewed the flow pattern around spheres. At low velocities the flow is approximately symmetrical, and the velocity then decreases on the downstream surface of the sphere. Separation of the flow occurs at Reynolds numbers of 14 to 24, and a very small, weak, torroidal vortex is formed near the rear stagnation point. At higher velocities the vortex strengthens and the separation ring advances toward the equator. Another transition occurs at Reynolds numbers of 130 to 500. The wake becomes unstable, oscillates about the axis of motion, and spills out its contents. Owing to the flow being axisymmetrical, the shedding takes place as a series of vortex loops.

A more recent photograph of the wake downstream of a sphere in a moving fluid (*8*) shows that in a considerable fraction of the wake close behind the sphere the residence time was greater than in the outer parts of the wake.

H. F. Johnson and co-workers (*22*) studied the effect of drop size and Reynolds number on the amount of material carried in the wakes of a single drop, flowing in a quiescent medium. They found that up to Reynolds numbers of 200, the volume of the wake increased as a 2.4 power of the drop volume. Above Reynolds numbers of 200 oscillation of drops was noted, and only a small fraction of the original material in the wake reached the top of the column, this fraction decreasing with increased length of column.

Hughes and Gilliland (*24*) explained the distortion of drops in a moving liquid by oscillations due to intermittent shedding of vortices.

A considerable fraction of the mass transfer to and from drops or solid spheres takes place on the downstream side of the drops (*11, 21*) to the torroidal vortex downstream of the drops or spheres (*13, 36*).

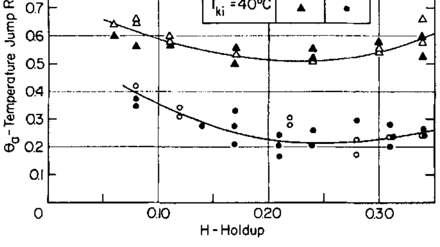

Fig. 4. Temperature-jump ratios as functions of holdup, ratio of flow rates, and temperature.

PROPOSED PHYSICAL MODEL OF HEAT TRANSFER IN A SPRAY COLUMN

The drop is formed in a water medium. As it rises, the drop velocity increases fast to the terminal velocity. After a drop travels a short distance, separation of the boundary layer takes place on the downstream side of the drop, a torroidal vortex is formed and grows, and the separation ring moves forward. The eddying motion of the continuous phase in the vortex sets up interfacial turbulence (*36*), which promotes high rates of heat transfer from the drop to the wake. The circulating core of the wake close to the drop reaches the drop temperature rapidly. Material from the wake initially at lower temperatures and later at the core temperature is shed downstream. New material from upstream of the drop enters the circulating core of the wake through the boundary layer.

The highest heat transfer rate from the drop to the wake takes place immediately after the formation of the wake. Conduction and convection, on the upstream side of the drop, are relatively small. Because of the long residence time of water in the core of the wake (*8*), the warmer material of the wake is shed and mixes with the water bulk only after the drops have resided in the column for a while. In this region the warm wakes are discharged into the bulk of the water, and the temperature of the water rises quickly. As the material of the wake is replaced, the resistance to heat transfer from the drop to the core of the wake is still low, but the temperature of the drop and the driving force are lower. In the upper section of the column the drop temperature becomes constant, and the rate of heat transfer diminishes to zero.

At the top of the column, below the interface, the holdup of the drops increases rapidly. The wakes are detached when the distance between the drops is diminished, and the rest of the water in the film surrounding the drops is expelled from the coalescence zone (*19*). During coalescence, more heat is transferred from the drops to the water, which is at a lower temperature than the drop, above the water inlet. The coalescence end effect contributes in some systems (*18*) 15 to 40% of the total concentration jump in the continuous phase and a corresponding concentration jump in the discontinuous phase. The water from the water inlet mixes rapidly as it comes in and loses its original identity, similarly to a liquid entering a highly mixed system.

In the continuous phase, at low holdup, longitudinal dispersion caused by the velocity profile prevails. As the holdup increases, the velocity profile of the continuous phase flattens (*26*), and longitudinal mixing of the continuous phase with water from shed wakes becomes predominant.

APPLICATION OF THE PHYSICAL MODEL TO THE DATA

The temperature profiles in Figures 1 and 3 fit the model. The range of Reynolds numbers in this work was 300 to 900, and shedding of wakes took place. The model explained the constant temperature of the water at the bottom of the column, the fast temperature change in the middle of the column, and the temperature jump at the water inlet.

At zero holdup, longitudinal dispersion of the continuous phase due to the velocity profile of the water is predominant, and the curves at different ratios of flow rates (Figure 4) should converge at that holdup.

At increasing holdup, the velocity profile is flattened. Mixing due to nonuniform velocity profile decreases, and mixing due to increased number of drops and amount of shed wakes increases. These two competing effects cause the minimum in Figure 4. The volume of wake carried with the drop is a function of drop diameter and velocity. The product of the two shows a minimum at the same range of holdups as the minimum of the jump ratio. The sharp increase of drop size at holdups above 0.20 is the main cause of the increase of the product of the drop diameter and the slip velocity and of the amount of mixing, for higher holdups.

At high holdups the slip velocity is low (Figure 2). At a given time the drops rise a smaller distance up the column than at low holdups. Therefore, shedding of the warmer wakes takes place lower in the column (Figure 3).

At the same holdup the total amount of water carried up the column in the wakes increases with increased ratio of flow rates, owing to the increased number of drops flowing up the column. Greater mixing of water from the wakes with bulk water and higher jump ratios result.

For holdups above 0.24 the jump ratio is exactly proportional to the ratio of flow rates. At these holdups, all mixing is caused by wakes shed into the bulk water and coalescence of drops. At the same holdup the amount of water in the wakes is proportional to the number of drops and hence to the ratio of flow rates.

No effect of temperature on the jump ratios was found, although the average viscosity of the water was different by about 12% for kerosene inlet temperatures of 35° and 65°C. This finding bears out that of Ebach and White (9), who found no effect of viscosity on eddy diffusivities in a packed bed, for one packing size and one fluid velocity, in the range of 1 to 26 centipoises. Cairns and Prausnitz (5) also concluded that the eddy diffusivity in a packed bed is independent of viscosity.

A possible explanation for the lack of temperature effect is that the drop diameters in Figure 2 were measured at room temperature. At higher temperatures the interfacial tension decreases, producing smaller drops. The reduced viscosity and the decreased diameter may have balanced each other.

APPLICATION OF THE PHYSICAL MODEL TO EXTRACTION SPRAY COLUMNS

The proposed physical model applies also to mass transfer. Mass is transferred from drops to wakes, which are shed and mix with the countercurrent continuous phase.

The equilibrium distribution ratio is unity for heat transfer, which results in one equilibrium line. For mass transfer the distribution ratio determines the distance between the concentration profiles of both phases at equilibrium.

TABLE 1. EFFECT OF COLUMN DESIGN AND CONCENTRATION ON CONCENTRATION-JUMP RATIOS

Solute concentration $C_w \times 10^3$ lb. mole/cu. ft.	Column *A* (*27*) $D_T = 1.41$ in. Run	θ_a'	Column *B* (*37*) $D_T = 1.53$ in. Elgin (*3*) design Run	θ_a'
10	19	0.325	27	0.37
20	17	0.31	21	0.30
30	1	0.325	19	0.31

Column length was 3.0 ft. Ratio of flow rates was 0.75

Concentration profiles of the continuous phase in extraction spray columns do not generally have a sigmoidal shape (*16, 17, 27, 37*). Secondary factors such as the amount of interfacial turbulence, mutual solubility, and surfactant additives affect the rate of heat or mass transfer from drop to wake; however, the concentration or temperature profile is determined primarily by the wake size and frequency of shedding. In longer columns, an approach to equilibrium at the top of the column can be expected.

In one experimental study concentrations of both phases were measured. Gier and Hougen (*18*) measured concentration profiles of adipic acid in water and diethyl ether in an extraction spray column. The fractional change in drop concentration, calculated from their data, for a distance of 22 cm. from the inlet nozzles (runs 11, 40-44), was 0.26 to 0.42. This change was continuous and was associated with a much smaller concentration change in the continuous phase, as predicted by the proposed model. The concentration of the continuous phase did not approach equilibrium at the top of the column, as the concentration of the drops was still far from equilibrium.

The jump ratio of the continuous phase at holdups below 0.06 (runs 40-43) was 0.50 to 0.55 for ratios of flow rates of 0.5 to 1.5, which is consistent with the expected behavior at low holdups.

Concentration jump ratios were calculated from two studies by Geankoplis and co-workers (*27, 37*) for two columns of same height and slightly different diameters as function of concentration (Table 1). No effect of either column design or concentration was noted. These two variables should not interfere with the mechanism of mass transfer by transfer from drops to wakes, wake shedding, and mixing in the range of concentration of their work.

Kreager and Geankoplis (*27*) studied the effect of column height on mass transfer rates. Their results are plotted in Figure 6 in the form of jump ratios as functions of column height for two flow ratios. The holdup was different in these runs, and therefore the effect of ratio of flow rates was probably compensated by the effect of holdup. The jump ratio for both curves was over 0.9 for a column length of 0.5 ft. The wakes, leaving the drops at the top of the column and mixing with the incoming water, were at the drop highest equilibrium concentration. As the column size decreased, the column approached the behavior of a single mixer.

CONCLUSIONS

The temperature, or concentration, jump ratios are a measure of the amount of mixing in the spray column.

At low holdups longitudinal dispersion due to continuous phase velocity profiles controls the amount of mixing in an extraction or heat exchanger spray column.

At high holdups the mixing in the continuous phase is caused by wakes of drops shed as the drops rise up the column.

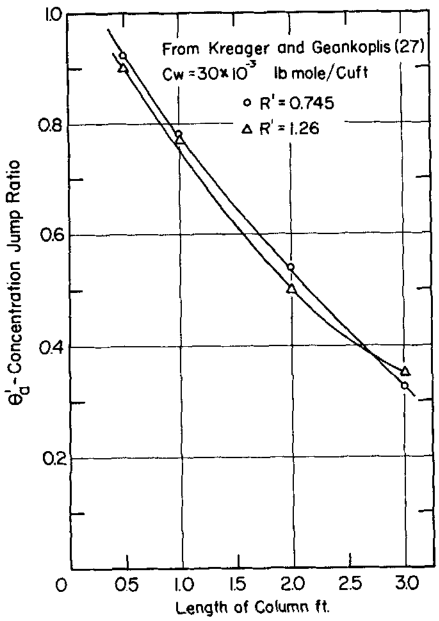

Fig. 6. Concentration-jump ratios as functions of column height (27).

Above holdups of 0.24 the temperature-jump ratio is proportional to the ratio of flow rates of kerosene to water.

As the column size decreases, it approaches the behavior of a perfect mixer.

A high proportion of heat is transferred from the drop to the wake at the bottom of the column. A high proportion of heat transfer by shed wakes to the bulk water occurs at the middle of the column.

ACKNOWLEDGMENT

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NOTATION

A = cross section of the column, sq. cm.
C_w = concentration of propionic acid in water, lb. mole/cu. ft.
D = mean drop diameter, cm.
D_T = diameter of column, in.
E_1 = longitudinal dispersion coefficient sq. cm./sec.
H = holdup of drops in the column
G_k = flow rate of kerosene, cc./sec.
G_w = flow rate of water, cc./sec.
R = ratio of flow rates of kerosene to water
R' = ratio of flow rates of methyl isobutyl ketone to water
t_{ki} = temperature of the kerosene at the dispersion plate, °C.
t_w = temperature of the water at any point in the column, °C.
t_{wa} = temperature of the water just below the water inlet to the column, °C.
t_{wi} = temperature of the water at the inlet, °C.
t_{wo} = temperature of the water at the outlet, °C.
V_s = slip velocity $= \frac{1}{A}\left[\frac{G_k}{H} + \frac{G_w}{1-H}\right]$ cm./sec.
θ = dimensionless temperature $= \frac{t_w - t_{wi}}{t_{wo} - t_{wi}}$
θ_a = temperature-jump ratio $= \frac{t_{wa} - t_{wi}}{t_{wo} - t_{wi}}$
θ_a' = concentration-jump ratio

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