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Direct Contact Heat Transfer with Change of Phase:

Spray-Column Studies of a Three-Phase Heat Exchanger

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Transfer characteristics are presented for a perforated plate-spray column in which a volatile dispersed phase evaporates while rising in the continuous, counterflowing, immiscible phase. Optimal column heights, volumetric transfer coefficients, holdup, and foam heights are reported as functions of flow rate and temperature approach for a pentane-water system, A comparison with related studies is presented.

Recently multiphase exchangers where latent heat rather than sensible heat is transferred between immiscible fluids have been effectively used in water desalination by direct contact freezing. Some of the technical and economical aspects of utilizing these multiphase exchangers were reported by Umano (*1*), Wiegandt (*2*, *3*), and others (*4*). Experimental direct freezing pilot plants (*5*) are presently in the process of accumulating valuable technical know-how.

Unlike the multiphase exchangers, where both the dispersed and the continuous fluids undergo change of phase, three-phase exchangers may be used for heat transfer at various temperature levels. The latter obviously depends on the choice of the transfer fluid. Stagewise operation of three-phase exchangers in a closed evaporation and condensation cycle was recently proposed by Harriott and Wiegandt (*6*) for simultaneous cooling and heating of sea water and desalined water streams in countercurrent flow. Some experimental data of condensation of methylene chloride in water flowing concurrently in a two-stage packed bed and a single-stage sieve-plate column were reported (*6*). Limited data were also reported on cocurrent flow evaporation of methylene chloride or pentane in water in a 2-in. diameter column. Wilke et al. (*7*) studied evaporation of water from sea water flowing concurrently in direct contact with hot Aroclor in an horizontal 3-in. pipe and steam condensation in direct contact with Aroclor in packed columns. Studies of condensation of steam in Aroclor in a simulated cocurrent spray column were also reported (*8*).

Despite increasing interest in technical information on direct contact heat transfer with change of phase, very little is known regarding the basic mechanism and heat transfer characteristics associated with evaporation of dispersions in immiscible liquids. Studies of single-drop evaporation in immiscible liquid media were recently reported by Sideman et al. (*9*, *10*). These, however, may not be directly extended to population of drops, where the onset of nucleation is not simultaneous (and should be dependent on the vapor holdup and degree of turbulence of the system) and where coalescence is bound to occur.

The following experimental work was undertaken as an attempt to study the transfer characteristics of a multidrop system under various operating conditions and, if possible, to relate these results to the single-drop studies. Particular attention was given to effects of flow rates and temperatures on the optimal column height, the volumetric transfer coefficient, and the holdup ratio. A pentane-water system was chosen for convenience of operation. However, based on earlier single-drop studies, it is believed the information obtained should reasonably apply for the butane-water system which is of more practical interest at the present.

Unlike the previously mentioned studies, countercurrent operation was chosen here. For a one-stage exchanger this insures higher efficiency and convenience of operation. The higher residence time of the droplets associated with counterflow operations would be expected to give lower optimal operating heights than in a comparable cocurrent flow study. It should, however, be noted that effects of temperature may offset this advantage, especially at low flow rates of the dispersed phase. The latter situation is, however, of little, if any, practical importance.

SOME BASIC RELATIONSHIPS AND DEFINITIONS

For three-phase exchangers operating at maximum volumetric efficiency, so that only latent heat is transferred, the following simple heat balance holds:

$$Q = G_c\, Cp_c\, (Tc_1 - Tc_2) = G_d L \tag{1}$$

It is noteworthy that, unlike the standard evaporators or condensors with metallic heat transfer areas, G_d is an independent operation variable. Assuming complete evaporation of the volatile liquid and a constant boiling point, one can calculate the outlet temperature Tc_2 for any desired flow rates and inlet temperature Tc_1.

The volumetric heat transfer coefficient is defined as

$$U_v = \frac{Q}{V\Delta T} \tag{2}$$

Evaluation of true temperature driving force would require knowledge of the temperature profile, which is usually not linear due to backmixing, in the column. This information, however, is rarely available in practice, where only inlet and outlet temperatures are known. Under these conditions, the true driving force is approximated by the log-mean temperature difference. Obviously, the latter approaches the former as backmixing disappears. In order to allow comparison with other related studies, the log-mean temperature differences will be used here. It may, however, be interesting to note that visual observations indicated no strong backmixing in this study.

The log-mean temperature driving force is defined as

$$\Delta T_{\ln} = (Tc_1 - Tc_2)/\ln\frac{Tc_1 - Td}{Tc_2 - Td} = \Delta Tc/\ln\frac{\Delta T_1}{\Delta T_2} \tag{3}$$

Equations (1) to (3) can be advantageously used to obtain expressions for the overall heat transfer rate for operation with constant inlet or outlet temperatures:

$$VU_v = G_c Cp_c \ln\frac{\Delta T_1}{\Delta T_1 - B(G_d/G_c)} \tag{4a}$$

and also

$$VU_v = G_c Cp_c \ln\frac{\Delta T_2 + B(G_d/G_c)}{\Delta T_2} \tag{4b}$$

where $B = L/Cp_c$. Equations (4*a*) and (4*b*) allow insight into the effect of the various operating variables on the overall heat flow rate. A detailed discussion of these effects is given elsewhere† (11).

For a given column cross section, knowledge of the height of the operating column Z is required to calculate the volumetric transfer coefficient. The optimal column height, defined as the column height in which evaporation is complete but no superheating of the vapors occurs, would thus yield the maximum transfer coefficient. This definition is clearly consistent with the heat balance and the ensuing equations presented above.

The average holdup ratio may also be of practical interest. This ratio of the volume of the dispersed phase to that of the total fluid volume is defined as

$$\bar{H} = \frac{1}{Z}\int_o^z H(z)dz = \frac{Z - Zc}{Z} \tag{5}$$

APPARATUS AND PROCEDURE

A schematic diagram of the apparatus is shown in Figure 1. It consisted of a double-wall vacuum insulated glass column, 70 mm. I.D., with top and bottom Plexiglas plates. To minimize visual distortions, the column was placed in a square Plexiglas container filled with water. Pictures of steel balls of known diameter taken in a similar 54-mm. column (9) showed that the horizontal distortion was almost completely reduced. The water coming from a constant head tank entered the column at the top water level through a perforated ½ in. pipe designed to minimize disturbances at the top of the column. The water flowed from the column through a circular opening around the pentane distribution plate and then into an intermediate level-control container. Electric heaters in the water sump tank as well as in the overhead tank allowed control of the inlet water temperature.

Pentane entered the column through a perforated plate. The pentane reservoir just below the perforated plate was surrounded by a water jacket to allow temperature control. Pentane was supplied from a constant pressure container and the flow was adjusted by valves. A preheater, consisting of a ¼ in. copper tubing coil wrapped with electric tape, was used to bring the pentane to the desired temperature. The distributing plate was made of an ebonite disk 3 mm. thick

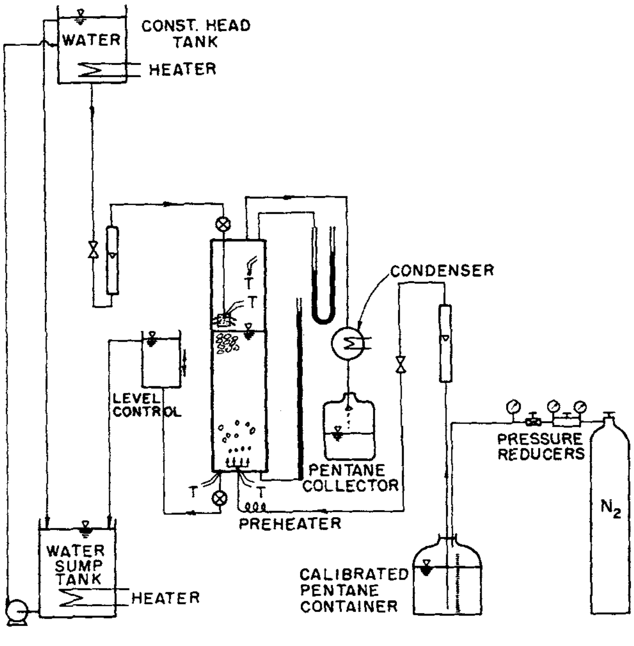

Fig. 1. Schematic diagram of experimental apparatus.

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† Material has been deposited as document 8679 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or 35-mm. microfilm.

and 50 mm. in diameter. The diameter of the holes was 0.5 mm. for all runs reported here. The number of holes varied with the pentane flow rates to insure identical pentane velocities in the nozzle. A rotameter was used to measure the water flow rate. The pentane flow rate was measured with a calibrated container and a stop watch. Temperature was measured with copper-constantan thermocouples. Although 1/100 of a degree could be read, the temperature readings were usually rounded off to 5/100. The maximum error introduced was estimated as ∓ 3%. However, because of small fluctuations of the column height, the maximum error of the results was estimated at ± 10%.

Heat losses from the column resulted in an apparent increase in the water temperature difference. These can be determined by operating the column without the dispersed phase. A correction plot (not shown here) was prepared by plotting the heat loss ΔQ per unit temperature driving force against the column height. Straight, almost parallel, lines were obtained when the parameter was the temperature difference between the average water temperature and the room temperature. Some losses of pentane through the water outlet were also inevitable, due mainly to the proximity of the water outlet openings to the pentane distributor. The experimental volumetric transfer coefficients were thus calculated by Equation (2) with Q, the heat flow rate, taken from the water-side heat balance as

$$Q = G_c Cp_c (Tc_1 - Tc_2) - \Delta Q \qquad (6)$$

The optimal height determination is based on the fact that at any column level below the optimal one, evaporation would not be complete and pentane liquid would concentrate at the top of the column. Thus, keeping the inlet conditions constant, the column level is changed and the temperature of the outlet water recorded. As long as these runs are conducted below the optimal level, the outlet water temperature will decrease with increase in the column level. The optimal level for certain operating conditions is thus determined as the level above which no change in temperature is noticed. Considering the sensible heat of the vapor compared with the latent heat of evaporation, a small increase of column level above the optimal height would hardly affect the water temperature.

The optimal level can also be determined by calculating the volumetric transfer coefficient directly from the experimental data [Equation (2)] for each run and by plotting it as a function of the corresponding column height, all other conditions being identical. The curves obtained have maxima with relatively moderate decrease of U_v with column height beyond the maximum. The column height corresponding to this maximum is obviously the optimal height. Agreement between these two methods is rather good, the maximum deviation being ±5%.

The holdup ratio was experimentally determined by simultaneously closing the inlet and outlet flows, and measuring the level of the column at shut-off Z, as well as the level of the water in the column Z_c, after all the pentane evaporated and disappeared.

The experimental range reported here is summarized in Table 1.

Table 1. Experimental Range

Flow rate, kg./min.	Superficial velocity,* cu. meter/(hr.) (sq. meter)	Velocity in orifice, cm./sec.
Pentane 0.042 to 0.107 × 10^{-3}	1.07 to 2.8	65 to 70
Water 0.59 to 1.30	9.3 to 20.3	

% mass flow ratio 3.3 to 18.3% pentane to water.

* Liquid, in empty column.

OPERATIONAL CHARACTERISTICS OF THE THREE-PHASE SPRAY COLUMN

The temperature driving force is not the only condition required for the evaporation of the drops in the continuous medium. Evaporation starts only after nucleation has set in in the droplet. Single-drop studies (9) indicate that at a given temperature difference, the onset of nucleation usually depends on the drop size, the external disturbances, and the degree of purity of the liquids involved. With instrument pure pentane no nucleation occurred in single drops of about 2 mm. diameter in distilled water, even in the presence of small nitrogen bubbles in the water. However, it was found that impurities in the volatile fluids and contamination normally associated with sea water, as well as the presence of very small gas bubbles artificially introduced into the water column, promoted nucleation. Hence, the tap water and technically pure (95%) pentane could be conveniently used throughout this work. No difficulties due to superheating were apparent during the continuous operation of the column, even with the smallest droplets. It is, however, noteworthy that superheating was apparent at the startup periods, especially at lower temperature differences. The drops then rose straight to the top without evaporation. Increasing the temperature and, sometimes, the flow rate of the inlet water, excited evaporation, which usually started at the top and propagated downward. The desired conditions could then be set and the data were taken after steady state conditions prevailed, usually after some 30 min.

The unusual characteristics of this three-phase exchanger merit a short description. When in normal operation, the height of the column Z consists of three distinguishable zones. These are shown schematically in Figure 2. The zone at the bottom is the free rising zone, where only a relatively small fraction of the droplets starts to evaporate, and the drops are seen to rise practically unhindered. The middle zone is the turbulent zone, where the dispersed phase holdup and superficial vapor velocity increase, due to the evaporation of the rest of the drops as well as the increase in bubble size. Some single evaporating drops may still be distinguished at the lower part of this zone in spite of the increased turbulence. Coalescence of the bubbles is also evident, mostly at the upper part. The upper zone consists mainly of foam, with very slight motion near the walls. The transition between these

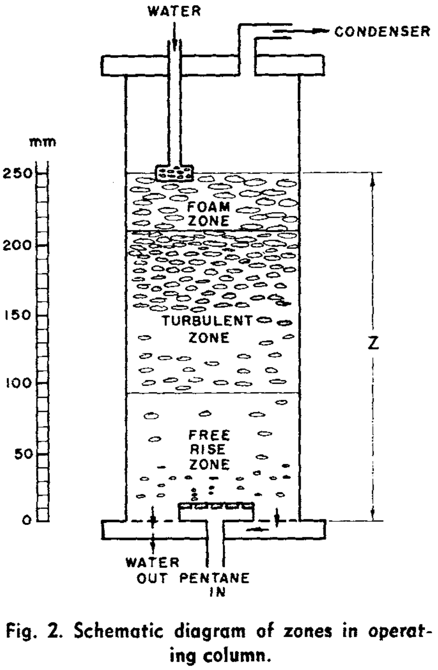

Fig. 2. Schematic diagram of zones in operating column.

zones is quite moderate, especially at high turbulent intensities associated with high pentane flows and high water inlet temperatures. On the other hand, the turbulent zone and turbulent intensity diminish and eventually disappear at very low water inlet temperatures and low column heights. In this extreme case most of the evaporation occurs after the droplets reach the top of the column and a pentane liquid layer may be formed at high pentane flow rates.

These observations are comparable to the streamline and turbulent regions noted in gas-liquid columns at different gas flow rates. They are also consistent with Fair's (*12*) studies of an air-water system in cocurrent flow, where single bubbles were noted to lose their identity at the high turbulence prevailing at superficial velocities above 6 cm./sec. The corresponding value for countercurrent flow may be expected to be somewhat lower. The superficial vapor velocity in this work varied between 6 to 16 cm./sec. It is obvious that the dispersed phase holdup varies along the column due to the longitudinal change of the superficial vapor velocity. It is interesting to note here that the holdup in air-water systems was found to be linearly dependent on the superficial gas velocity up to approximately 6 cm./sec. Above this value, the holdup increases rather moderately with the superficial velocity and an asymptotic approach to a maximum value is indicated by the curves (*12*). This deviation from linearity is undoubtedly closely related to flooding conditions. By analogy to the air-water experiments, it may be assumed that in most of the work conducted here, the column operated, at least at its upper part, above the flooding conditions.

EXPERIMENTAL RESULTS

The Optimal Column Height

Increase in the dispersed phase flow rate considerably increased the required optimal column height (Figures 3 and 4). This is consistent with the corresponding increase in the total heat throughput and is apparently due to the increase in the superficial vapor velocity and coalescence of the drops in the column. The turbulent and "foam" zones increase accordingly.

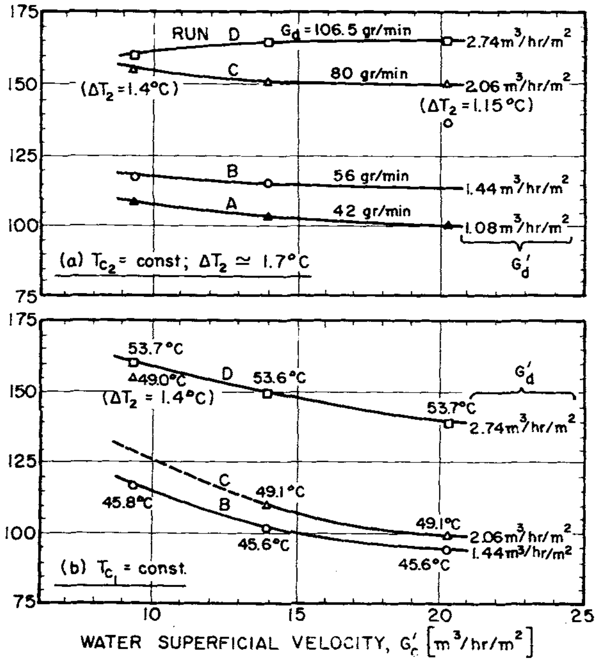

Fig. 3. Effect of flow rates on optimal column height. (*a*) T_{c2} = constant. (*b*) T_{c1} = constant.

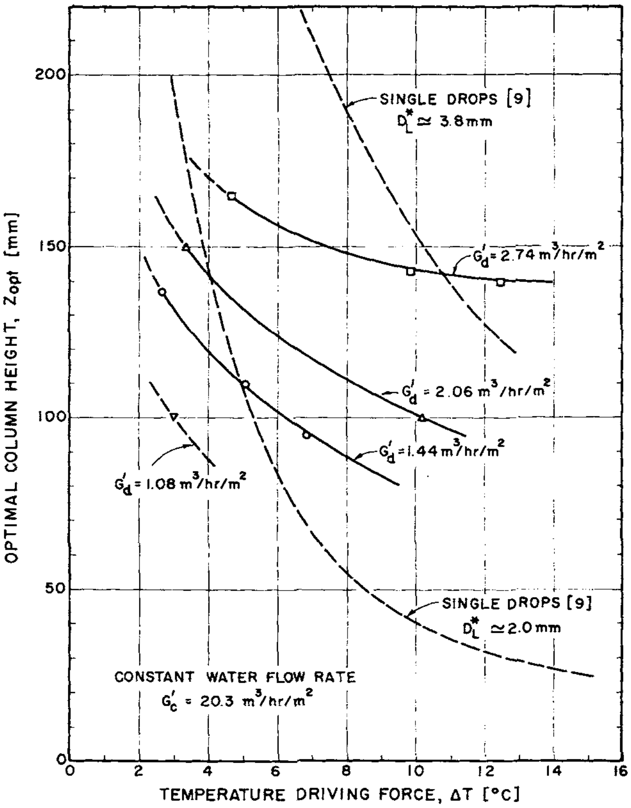

Fig. 4. Effect of temperature driving force on optimal column height.

The effect of the continuous phase flow rates on the optimal height is rather small, especially when operating with a constant outlet temperature Figure 3*a*. The decrease of the optimal height with increase of the continuous phase flow rate is much more pronounced when the inlet temperature is kept constant, since both the velocity and temperature driving force act in the same direction. Some of the experimental data are presented in Table 2.†

The optimal height as a function of the log-mean temperature driving force is shown in Figure 4 for various pentane flow rates at a constant water flow rate. As is to be expected, all the curves seem to go to infinity as ΔT goes to zero, and the optimal height decreases as ΔT increases. Single-drop data are included for comparison.

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† See footnote on page 297.

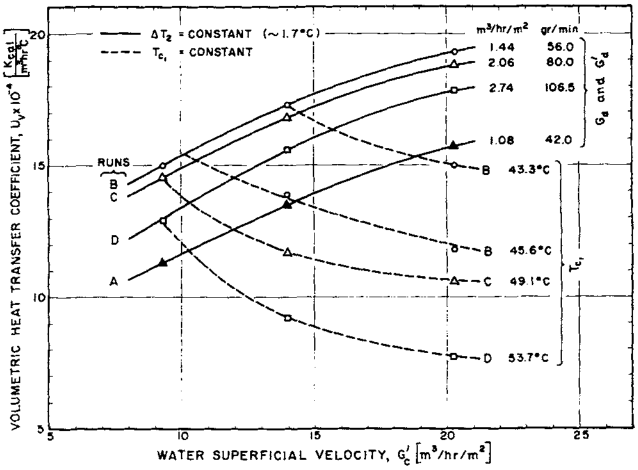

Fig. 5. Volumetric heat transfer coefficient as a function of G'_c at various pentane flow rates.

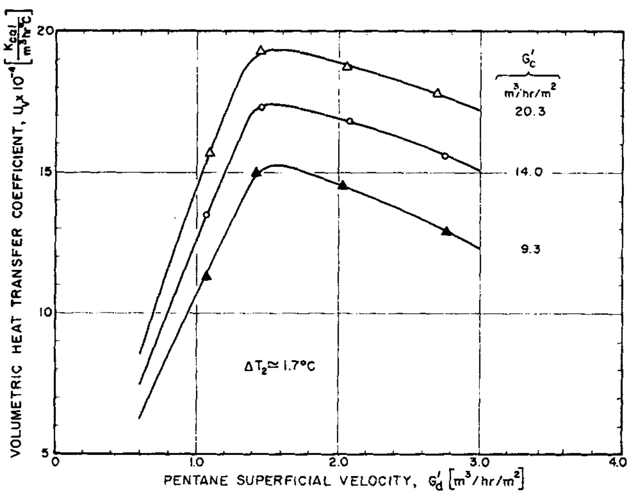

Fig. 6. Volumetric heat transfer coefficient as a function of G'_d at various water flow rates. ΔT_2 = constant.

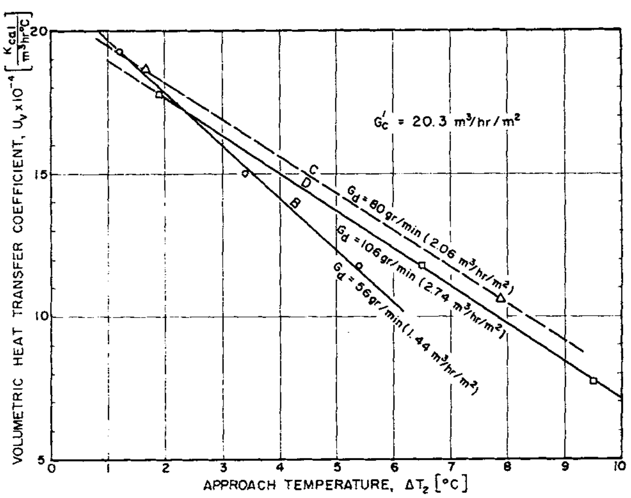

Fig. 8. Volumetric heat transfer coefficient as a function of ΔT_2. G_c = constant.

Volumetric Heat Transfer Coefficients

Some of the experimental data are presented in Table 2. Figure 5 represents the volumetric transfer coefficient as a function of water flow rate for various pentane flow rates, all at constant outlet conditions ($\Delta T_2 \simeq 1.7$°C.) In general, the dependence of U_v on G_c is similar to that of VU_v (Figure 11). However, flatter curves are seen here, since the optimal volume decreases with G_c at constant inlet temperatures.

The pronounced effect of G_d on the optimal column height greatly affects the volumetric heat transfer coefficients. The transfer coefficient is seen in Figure 6 to pass a maximum at G_d of about 1.5 cu. meter/(hr.)(sq. meter) and to decrease moderately at high pentane flow rates.

A more general description of the operating characteristics is obtained by plotting U_v vs. the ratio of the mass flow rates. Figure 7 clearly indicates two operating ranges. The general characteristics of the volumetric transfer coefficient in the first range are similar to those of a liquid-liquid spray column. The transfer coefficients increase with increasing the flow ratio (G_d/G_c). The second range is obviously above the normally defined flooding point but, unlike liquid-liquid systems (*13*), the transfer coefficient decreases with increasing the flow ratio. As is evident from Figure 7, the G_c = constant curves converge to some asymptotic value which cannot be surpassed by increasing the dispersed phase flow rate.

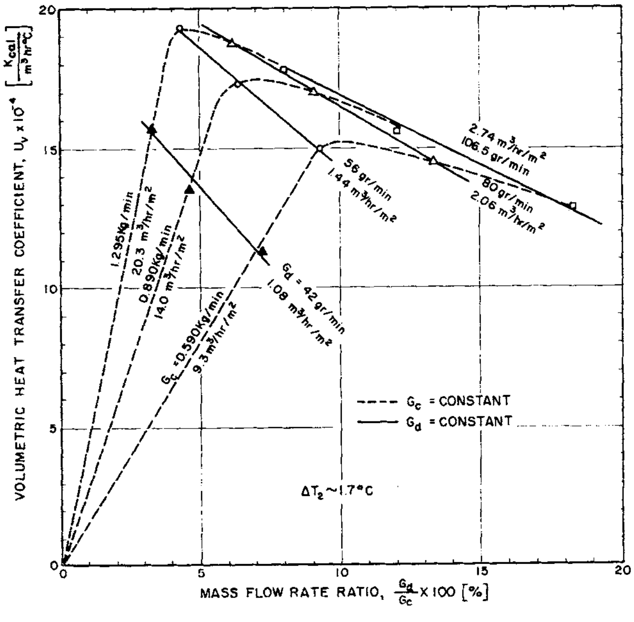

Fig. 7. Volumetric heat transfer coefficient as a function of G_d/G_c. ΔT_2 = constant.

Unlike surface heat transfer coefficients of single drops (*9*), the volumetric heat transfer coefficient was found to be strongly dependent on the temperature driving force. It is particularly affected by the approach temperature, since the latter strongly affects the optimal volume as well as the log-mean driving force. The latter is highly sensitive when $\Delta T_1 >> \Delta T_2$, especially as $\Delta T_2 \rightarrow 0$. [For example, the value of VU_v (Figure 11) at G_d = 56 g./min. and G_c = 1.3 kg./min. is 94% larger when ΔT_2 = 0.5°C. as compared with 1.7°C.] The volumetric transfer coefficients increase with decreasing ΔT_2. This relationship, shown in Figure 8, seems to be linear in the experimental range studied here, which is consistent with a finite value of U_v as $\Delta T_2 \rightarrow 0$.

The interrelation between the pentane flow rate and the approach temperature ΔT_2 can be seen by cross plotting Figure 8. The two (increasing and decreasing U_v) ranges previously seen are evident. The transition point corresponding to U_v max. is clearly seen to be dependent on the approach temperature. The closer the approach the smaller the pentane flow rate required to yield U_v max.

The Dispersed Phase Holdup

As is evident from Figure 9, the overall effect of column height on the holdup is rather minute. The continuous phase flow rate has a relatively small effect on the holdup ratio. This is quite understandable in view of the effect of the water flow rate on the temperature driving force. Thus, whereas the effect of G_c on $\bar{H}$ is quite significant when operating at constant inlet temperature, holdup at constant outlet temperature seems but slightly affected by changes in G_c.

The dispersed phase flow rate affects the holdup ratio appreciably both at Tc_1 = constant and Tc_2 = constant. It is interesting to note that at the lower pentane flow rates, holdup decreases with increase of column height. This is most probably due to the relatively large effect of the foam layer which seems to change but slightly with change of column height (the turbulent zone under these conditions is quite small).

It is noteworthy that unlike liquid-liquid exchangers, the maximum volumetric transfer coefficient does not coincide with the maximum holdup ratio. As seen in Figure 9, the latter was actually never reached in this work.

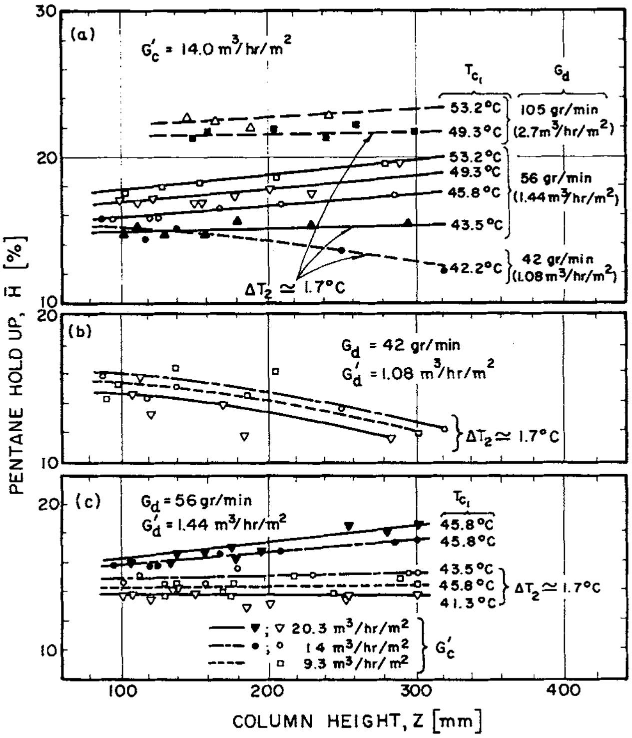

Fig. 9. Effect of flow rates on dispersed phase holdup ratio. (*a*) G_c = constant. (*b*) and (*c*) G_d = constant.

The Foam Layer

Measurement of foam layer height was undertaken to allow for future comparison with other studies in columns of different diameters. Accurate measurement of the foam height was rather difficult as the transition from the turbulent zone was quite moderate. The data obtained may serve to give a good indication as to the effect of the main variables on this foam layer. To facilitate visual observation, the water was slightly tinted with blue water-soluble pigment.

Figure 10 represents the effects of the water and pentane flow rates, at various temperatures, on the foam layer at various column heights. In general, increase in the water inlet temperature, pentane flow rate, and column height is seen to increase the thickness of the foam layer. At low pentane flow rates, the foam thickness is quite constant with a slight increase with column height. The effect of the pentane flow rates is pronounced at constant outlet temperature, mainly due to simultaneous increase in the average column temperature. As seen throughout this work, water flow rate seems to be a minor variable and its effect on the foam layer is quite small. However, a change in the water flow rate affects the average column temperature. The effect of temperature is quite pronounced.

DISCUSSION

The particular characteristics of the direct contact three-phase heat exchanger, where the transfer area varies with the operating conditions and the boiling point is (assumed) constant, allows direct evaluation of VU_v, the overall heat transfer rate, as a function of the operating conditions [Equation (4)]. The accuracy of these overall rates depends on that of the temperature driving force. The log-mean temperature difference, used in this system for convenience, seems to be suitable for practical applications where only inlet and outlet conditions are usually known. The agreement between overall rates calculated from Equation (4) and those calculated from the experimental data shown in Figure 11 serves to indicate the degree of accuracy of the experimental work rather than the validity of the theoretical treatment. Somewhat larger deviations between the experimental and theoretical values [calculated by Equation (4)] were noted in the constant water flow rate runs.† These are most probably due to the large effect of the pentane flow rate on the turbulent intensity in the column, which affects the optimal column height as well as the heat transfer coefficient. Referring again to Figure 11, it is noteworthy that curves B of constant ΔT_2 are the locus of all points of optimal operating conditions.

The use of the average boiling point T_d in calculating the driving forces may lead to errors, especially when operating at low approach temperatures and high column heights; 2.56 mm. Hg affects the boiling point of pentane by 0.1°C. In this study the true boiling point at the bottom was larger than the average T_d by 0.2°C. at the most, and the estimated error is up to 5%. Estimation of errors is complicated in view of the nonlinearity of the boiling temperature along the column, since the static head is a function of the dispersed phase holdup which obviously varies along the column. Thus, the true approach ΔT^*_2 would be smaller than the given apparent ΔT_2. The significance of this fact is amplified by the fact that the required optimal height increases sharply at closer approaches.

The effect of the temperature driving force on the optimal height is closely interlinked with the flow rates, especially that of the dispersed phase. Figure 4, where the heights of evaporation of single pentane drops in stagnant, constant temperature water are included for comparison, allows some insight into the effects of drop interaction associated with these parameters. It should be emphasized that identical nozzle velocities of pentane were used in all the spray-column studies reported here. Hence, one can reasonably assume that the initial diameter of the pentane liquid drops were the same in all the runs. Pictures taken indicate the initial drop diameter to be approximately 1.40 mm. (Use of the Hayworth and Treybal correlation gives the value of 1.65 mm. for initial liquid drop diameter.) The corresponding curve for single drops of this size would undoubtedly lie to the left and below the curve for the 2 mm. drops shown in Figure 4. This is consistent with the data for the lower pentane flow rates where the turbulent and foam zones were relatively small.

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† See footnote on page 297.

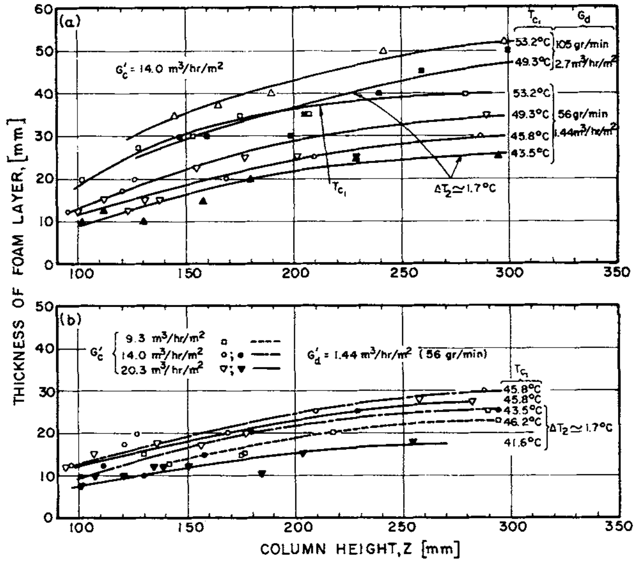

Fig. 10. Effect of operating variables on foam height. (*a*) G_c = constant. (*b*) G_d = constant.

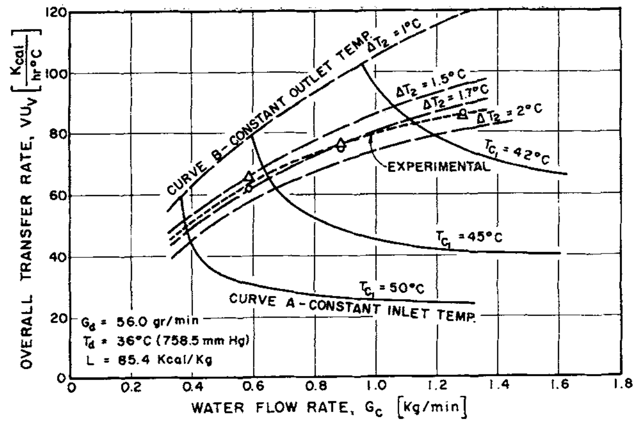

Fig. 11. Overall heat transfer rate as function of G_c. G_d = constant.

Interpolating between the single-drop data in Figure 4 indicates that larger diameters would correspond to the higher optimal heights associated with higher pentane flow rates. This is consistent with increased coalescence. Also noteworthy is the observation that the greater the coalescence of the bubbles, the smaller is the effect of the temperature driving force on the optimal column height. The higher turbulence associated with larger temperature differences, which should decrease the time, hence the height, of evaporation, seems to be counterbalanced by increased coalescence of the drops and bubbles. Put in practical terms, this may mean that unless coalescence is prevented by external forces, the initial drop diameter has but little effect on the optimal column height if the column is operated at high pentane flow rates and relatively large, say above 5°C., temperature differences.

The prominent effect of ΔT_2 on the optimal column height, especially at low values of ΔT_2, is indicated by the point (open circle) of curve *B* in Figure 3*a* which was obtained with $\Delta T_2 = 1.15°C.$, as compared with the points of curve *B* which were obtained with $\Delta T_2 \simeq 1.7°C.$ Similarly, Figure 3*b* the (triangular) point at a pentane flow rate of 2.06 cu. meter/(hr.)(sq. meter) deviates from the otherwise consistent data. This point corresponds to ΔT_2 of 1.4°C.

Pentane inlet temperature was not an experimental variable in this study and the pentane liquid was usually introduced between 1.5° to 1.8°C. below the average (for static head) boiling temperature in the column. Higher inlet temperatures result with evaporation in the distributing plate and vapor-blocking disturbed continuous, steady state operations. Since the ratio of sensible to latent heat is 0.7% per °C., the error introduced in neglecting this subcooling effect on the heat balance is rather small. Subcooling in single evaporating drop studies (*9*) and superheating in the cocurrent sieve-plate column studies (*6*) hardly affected the temperature driving force. However, the optimal column height is certainly affected by the dispersed phase inlet conditions, since these greatly affect the height of the free rising zone. Sideman and Hirsch's theoretical analysis of single evaporating drops indicated that the volatile liquid should be introduced into the water at least saturated and preferably slightly vaporized, thus considerably reducing the size of the exchanger (*10*). Indeed, only slight superheating of the pentane caused evaporation to start in the pentane distributor and the free rising zone was practically diminished. Somewhat similar effects of superheating on the evaporation level were also noticed in the cocurrent flow sieve-plate evaporator (*6*).

It is important to note that the troublesome effects of superheating noted in our apparatus would hardly affect large-scale equipment and an appreciable reduction in the free-rise zone is quite feasible.

The volume taken up by the foam is considered to be rather ineffective as far as the heat transfer process is concerned. In view of the increase of the foam zone with increasing G_d, one may suspect that the actual operative volume is smaller than the apparent measured volume. With the assumption that the foam height is 20 mm. on the average, the true transfer coefficients are probably higher by some 15% than those reported here. Moreover, since it is quite reasonable to assume that wall effects are quite large in the experimental column used here, one would expect lower foam heights in larger industrial size columns. Thus, the data presented may be considered conservative.

Comparison with Other Spray-Column Studies

The volumetric transfer coefficients obtained in this study favorably compare with those reported in previous two-phase spray-column studies (*13* to *19*) in which heat was transferred between water and organic liquids. A detailed tabular comparison (Table 3) is available elsewhere.† In general the maximum heat transfer coefficients reported in these two-phase studies are about one half of those reported here, whereas the dispersed phase flow rates are twenty- to one hundred-fold larger. Not included in this comparison are the studies of CCl_4—water system of Johnson et al. (*20*), which yielded order of magnitude lower volumetric coefficients. Also omitted is the extensive study of Pierce et al. (*21*) of a mercury-water system in which transfer coefficients larger by order of magnitude than those obtained in the organic-water systems are reported.

The volumetric transfer coefficients obtained here varied between 10×10^4 and 20×10^4 kcal./(cu. meter) (hr.) (°C.) [6.2×10^3 to 12.5×10^3 B.t.u./(cu. ft.) (hr.) (°F.)]. However, since the approach temperature used here was only about 1.7°C., larger coefficients may be obtained in practical systems operating with closer approaches. Reduction of the height of the free rising zone as well as that of the apparently inactive foam would also effect larger transfer coefficients. Harriott and Wiegandt (*6*) reported the value of 270×10^4 kcal./(cu. meter) (hr.) (°C.) [17×10^4 B.t.u./(cu. ft.) (hr.) (°F.)], based upon exit temperature driving force of 0.5°C. (and probably lower) and active froth volume, for their cocurrent sieve-plate evaporator. Coefficients of similar magnitude were reported (*6*) for packed-bed condensers and twice as large for a cocurrent sieve-plate condenser.

Second to the approach temperature, the dispersed phase flow rate was found to be the most important parameter. The effect of the continuous phase flow rate on the overall transfer coefficient (as well as on the other variables studied here) was found to be relatively small. This is very similar to liquid-liquid spray-column exchangers, where at any given dispersed phase flow rate the volumetric heat transfer coefficient was only slightly affected by the continuous phase flow rate. As in the liquid-liquid exchangers, the flow rate ratio was found to be an important characteristic parameter. At low pentane flow rates, however [up to about 1.5 cu. meter/(hr.) (sq. meter)], the volumetric transfer coefficient increases with increasing pentane-water flow rate ratio; the volumetric transfer coefficient then decreases with increased pentane flow rate. The maximum point was found to be dependent on the flow rate as well as on the approach temperature. The general characteristics of these two regions are similar to standard liquid-liquid spray-column exchangers operating below and above flooding conditions.

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† See footnote on page 297.

CONCLUSIONS

Experimental studies of a pentane evaporating in water in a countercurrent spray column provide some insight into the transfer characteristics of multiphase heat exchangers. Effects of flow rates and temperatures on optimal column heights, volumetric heat transfer coefficients, holdup, and foam height were investigated in a 70 mm. I.D. glass column. Except for very low pentane flow rates, the column operated under turbulent conditions, with a foam layer above the turbulent zone.

The optimal height was found to differ from that found earlier for equivalent single drops. The higher the pentane flow rate, the higher the deviation and the less the apparent effect of the temperature driving force. In general, the optimal height varied between 100 and 160 mm., increasing with increase of pentane flow rate and with decrease of the exit approach temperatures. The effect of the water flow rate is relatively small.

The volumetric transfer coefficients varied between 10×10^4 to 20×10^4 kcal./(cu. meter) (hr.) (°C.) [6.2×10^3 to 12.5×10^3 B.t.u./(cu. ft.) (hr.) (°F.)], with approach temperatures exceeding 1.7°C. The dependency of the maximum transfer coefficient on the mass flow ratio and the approach temperature for this system was obtained.

The pentane holdup ratio varied between 15 to 22%. It was found to vary with the pentane flow rate and column temperature but was little affected by water flow rate and overall column height. The thickness of foam layer, found to be somewhat dependent on the column height, as well as on the temperature and the pentane rate, varied from 10 to 50 mm. Studies on wall effects are required before the data obtained here can be accurately applied to units of different sizes.

It is indicated that columns with larger diameters, better design, and much closer temperature approaches would yield much higher transfer coefficients. Introduction of some mixing device into the system would increase turbulence and give a more uniform distribution of the dispersed phase, thus favorably affecting the optimal active volume as well as the transfer coefficients (22). Work in this direction is presently underway.

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NOTATION

B = latent to specific heat ratio
C_p = specific heat capacity
D^*_L = initial drop diameter (Figure 4)
G = mass flow rate, g./min. or kg./min.
G' = superficial velocity, cu. meter/(hr.) (sq. meter)
H = holdup of dispersed phase
$\overline{H}$ = holdup of dispersed phase, average
L = latent heat of evaporation
Q = heat flow rate
ΔQ = heat losses from column
T = temperature
Tc = temperature of continuous phase
Td = temperature of dispersed phase
U = heat transfer coefficient, (kcal.) (hr.)/(sq. meter) (°C.)
U_v = volumetric heat transfer coefficient, kcal./(hr.) (cu. meter) (°C.)
VU_v = overall heat transfer, kcal./(hr.) (°C.)
V = volume of operating column
Z = height of operating column
Z_c = height of water column
ρ = specific density

Subscripts

1 = water inlet side
2 = water outlet side
c = continuous phase, water
d = dispersed phase, pentane
max = maximum value
min = minimum value
opt = optimal value

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