Solids," 2nd ed., p. 493, Oxford at the Clarendon Press, England (1959).
5. Crider, J. E., and A. S. Foss, submitted for publication (1965).
6. ———, *Univ. California Radiation Lab. Rept. UCRL-11757* (January, 1965).
7. Deans, H. A., and Leon Lapidus, *A.I.Ch.E. J.*, **6**, 656 (1960).
8. Frazer, R. A., W. J. Duncan, and A. R. Collar, "Elementary Matrices," pp. 78-79, Cambridge at the University Press, England (1952).
9. Grantmacher, F. R., "The Theory of Matrices," Vol. 2, p. 63, Chelsea, New York (1960).
10. Kjaer, Jørgen, "Measurement and Calculation of Temperature and Conversion in Fixed-Bed Catalytic Reactors," pp. 74-75, Jul. Gjellerups Forlag, Copenhagen (1958).
11. Petersen, E. E., "Chemical Reaction Analysis," pp. 225-229, Prentice-Hall, Englewood Cliffs, N. J. (1965).
12. Quinton, J. H., and J. A. Storrow, *Chem. Eng. Sci.*, **5**, 245 (1956).
13. Singer, Emanuel, and R. H. Wilhelm, *Chem. Eng. Progr.*, **46**, 343 (1950).
14. Wehner, J. F., and R. H. Wilhelm, *Chem. Eng. Sci.*, **6**, 89 (1956).

Manuscript received February 23, 1965; revision received June 11, 1965; paper accepted July 23, 1965.

Direct Contact Heat Transfer with Change of Phase: Condensation of Single Vapor Bubbles in an Immiscible Liquid Medium. Preliminary Studies

SAMUEL SIDEMAN and GIDEON HIRSCH

Technion, Israel Institute of Technology, Haifa, Israel

Motion picture studies of condensation of isopentane bubbles rising in water elucidate the transfer mechanism involved in latent heat transport.

In general, two characteristic regions are noted. In the first region, up to some 80% liquid content, the bubbles deform and oscillate and heat is transferred by turbulent convection. In the second region the rate of transfer is controlled by the resistance of the condensed liquid, and heat is mainly by conduction. The effect of temperature differences between the bubble and the continuous phase (up to 3.5°C.) on the transfer coefficients could not be isolated, whereas that of the initial diameter of the bubble was quite marked.

The results are in agreement with those obtained in earlier studies of evaporating drops in immiscible liquids, indicating the similarity of the basic heat transfer mechanisms.

Condensation of vapors in immiscible liquid media as a means of latent heat transport has recently gained importance in connection with water desalination projects. This operation is usually coupled with an earlier stage of direct-contact evaporation, the two operations in series forming a closed thermodynamic cycle. In essence, this cycle is similar to the standard refrigeration cycles, with the important omission of the metallic heat transfer surface between the phases. The temperature level, as well as the fluid used as the dispersed phase, may, however, vary according to whether water vapor or ice is the (intermediate) product required. The advantages of this mode of operation over conventional heat transfer techniques are summarized in our earlier work on direct-contact evaporation (*1*, *2*).

Previous work (*3* to *6*) on condensation of vapors in immiscible liquid was aimed mainly at obtaining volumetric transfer coefficients in packed columns, in cocurrent pipe flow, and in simulated spray columns. Condensation of isobutane in an ice-packed column was reported by Wiegandt (*3*). Heat transfer coefficients per column cross section were reported to vary from 5,000 to 3,300 kcal./(hr.) (°C.) (sq. meter) with a temperature difference from 1° to 3°C. Condensation studies in water-ice slurries in a 2-in. column indicated that condensation rates increased with increasing ice content in the slurry. With butane feed of 1.24 lb./sq.ft. (column cross section) and an average temperature difference of 3°C., the overall heat transfer coefficient was reported as approximately 10,000 kcal./(hr.) (°C.) (sq. meter).

Condensation of steam in Aroclor in countercurrent packed beds and in cocurrent flow in a pipe using a Venturi as a mixing device was reported by Wilke (*4*) and Lackey (*5*). For the packed-bed column experimental H.T.U. (height of transfer unit, liquid controlling resistance) varied between about 25 and 50 cm. for Aroclor flow rates of about 7.5×10^4 to 15×10^4 kg./

Samuel Sideman is on sabbatical leave at Oklahoma State University, Stillwater, Oklahoma. Gideon Hirsch is with the Israel Atomic Energy Commission, Demona, Israel.

(hr.)(sq. meter) respectively. The apparent volumetric transfer coefficients for the Venturi mixer were 2.4×10^6 to 6.4×10^6 kcal./(hr.)(°C.)(cu. meter). Lower values were obtained with a simulated cocurrent spray column. A packed-column design procedure for gasoline condensers was suggested by Hu (*6*) and a corrected version by Wilke and Lackey (*5*).

Condensation studies of methylene chloride flowing cocurrently with water in a packed bed and a sieve plate were recently reported by Harriott and Wiegandt (*7*). Basing their calculation on froth volume and on the exit approach temperature, they reported values up to 6.4×10^6 kcal./(hr.)(°C.)(cu. meter) for the sieve plate condenser. Lower coefficients, up to 2.4×10^6 kcal./(hr.)(°C.)(cu. meter) at a flow rate of 19.5×10^4 kg./(hr.)(sq. meter), were reported for the packed-bed condenser.

The better performance of the methylene chloride sieve plate as compared with the simulated Aroclor spray column may to a large extent be due to the difference in the physical properties affecting the size of the bubbles. Spray-column type of exchangers are usually more efficient than packed beds for systems yielding small drops and therefore have higher transfer area per unit column volume.

The related studies of Bankoff and Mason (*8*) on latent heat transport from a train of steam bubbles (2,500 cycles/sec.) to a countercurrent, submerged water jet help to shed light on the physical characteristics of condensing single bubbles. On the basis of steam flow rate, water temperature, and velocity, they reported three distinct types of bubble behavior: (1) ellipsoidal bubbles with smooth surfaces at low steam rates and high temperature differences (50° to 70°C.); (2) ellipsoidal bubbles with irregular surfaces at increased steam flow rates and 50°C. temperature difference; (3) irregular bubbles, which, unlike the first two groups, did not completely collapse at the lower temperature differences (15° to 30°C.). The heat transfer coefficients for all three groups varied between about 6.5×10^4 and 15×10^6 kcal./(hr.)(cu. meter)(°C.), while the (bubbles) Reynolds numbers varied between 172 and 14,000.

Bankoff's values compare favorably with those reported by Grassmann and Wyss (*9*), who studied heat transfer between noncondensing, or rather partially condensing, steam bubbles and water. With a bubble frequency of about 20 cycles/sec. they obtained water-side transfer coefficients ranging from 6.8×10^4 to 9.8×10^4 kcal./(hr.)(sq. meter)(°C.). The difference between Grassmann's and Bankoff's results is undoubtedly due to the much higher turbulence of the latter's system.

The mechanism of transfer and the transfer coefficients per unit area of single drops of an immiscible volatile fluid evaporating in water have been reported earlier (*1, 2*). The orders of magnitude of the instantaneous heat transfer coefficients related to the total interfacial area of the rising two-phase drop were 1,000 to 2,000 kcal./(hr.)(sq. meter)(°C.) for $D_L^* = 3.5$ mm. and 2,500 to 3,500 kcal./(hr.)(sq. meter)(°C.) for $D_L^* = 2.0$ mm. Transfer coefficients larger by one order of magnitude were obtained when these were related to the initial areas of the liquid drops.

In the present work an attempt is made to study the complementary part of this "refrigerating" cycle and to compare the transfer mechanism as well as the surface transfer coefficients in condensation and evaporation of single bubbles. It should, however, be clearly understood that the condensation data presented here are related to the free rise period of the condensing bubbles, after their release from the nozzle. The "initial bubble diameter" referred to here denotes the diameter of the bubble detaching itself from the nozzle.

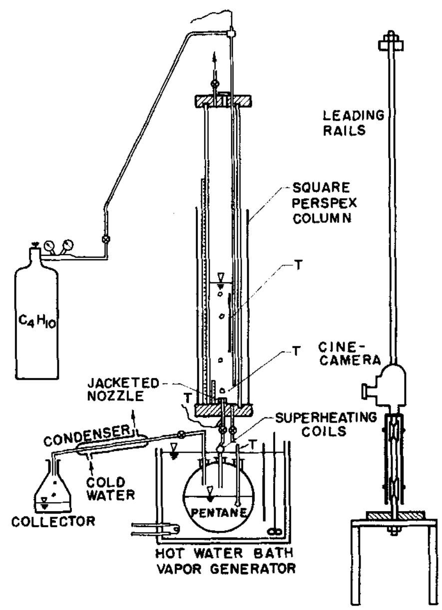

Fig. 1. Schematic diagram of apparatus. Isopentane-water system.

EXPERIMENTAL

The experimental apparatus (Figure 1) consisted of a doubled-wall vacuum-insulated glass column, 54 mm. I.D., with top and bottom Plexiglas plates. To minimize visual distortion, the column was placed in a square Plexiglas contained filled with water, thus reducing the horizontal distortion from 1.3 to 1.003. Single isopentane bubbles were introduced through a jacketed Plexiglas nozzle set in the bottom plate. The nozzle design was similar (though much larger) to the one used for the evaporating-drop studies (see *1*, Figure 8). By circulating hot water through the jacket of the nozzle, the vapor was insulated from the cold water in the column. Vapor coming out of the generator was superheated by electric coils wound around the ¼-in. copper tube leading to the nozzle. A fine thermocouple (40 S.W.G. copper-constantan) was inserted through the center at the nozzle outlet. By varying the heat load on the vapor line and in the jacketed nozzle, the temperature of the bubble could be controlled. Water temperature was determined by another copper-constantan thermocouple mounted near the nozzle outlet and was checked by a calibrated mercury glass thermometer immersed in the column. Before each run the water was mixed by a turbulent stream of butane gas. The drops were photographed with a Paillard-Bolex H-16 Reflex Cine-Camera, using a 85-mm. pan cinor lens with a 5-mm. extension tube. A special stand moving on vertical rails permitted the bubbles to be followed with the camera along the column. Rear lighting through a horizontal grid allowed better observation of the volatile liquid phase (*10*). By analyzing consecutive pictures of each run, the volume, area, and velocity of the drops could be conveniently determined at various heights and the heat flux and transfer coefficients calculated. The expected range of the experimental error was up to ± 0.1°C. for temperature, up to 0.002 cm. for the bubble diameter, and up to 0.02 sec. for time.

Two different nozzles, 3 and 6 mm. I.D., were used in this work, resulting in two initial bubble diameters of about 3.8 and 5.5 mm., respectively. The smaller bubbles were photographed at a speed of 59 ± 1 frames/sec. and the larger bubbles at 51 ± 1 frames/sec.

RESULTS AND ANALYSIS

Data were obtained by direct measurement of enlarged (20×) consecutive pictures developed from the motion picture films. As was to be expected, the greatest changes in volume and area occurred at the initial stages of the condensation process. The small bubbles ($D_v^* \simeq 3.8$

mm.) usually appeared as ellipsoids, with relatively small fluctuation in shape. On the other hand, the larger bubbles ($D_v^* \simeq 5.5$ mm.) deformed appreciably, appearing in various shapes such as disks, cones, etc. Some of these shapes are shown in Figure 2, which represents a typical sequence of condensation of the larger bubbles.

Time-Dependence of Area, Volume, and Vapor Content

Earlier studies of evaporation of single drops showed that the vapor phase concentrates at the top of the volatile liquid drop. The volatile liquid at the bottom of the two-phase drop could not be seen above some 5 to 10 wt. % vapor content. This liquid layer, however, was observed in the present condensation studies only at relatively large temperature differences (about 25°C.), an indication that the condensation was not complete at the relatively low range of temperature differences (0.6° to 3°C.) employed in this work. When some air was introduced into the vapor generator, a gaseous cap did appear at the top, and the condensed liquid could be seen at the bottom of the condensing bubble.

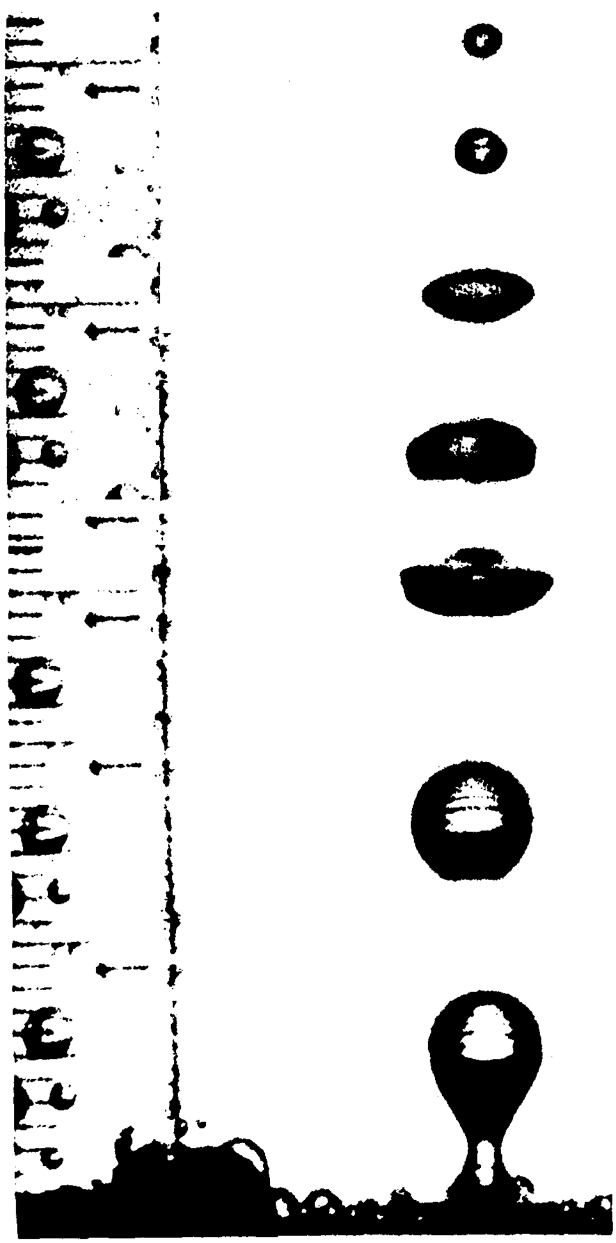

Fig. 2. Typical condensation sequence. Large ($D_v^* \simeq 5.5$ mm.) isopentane bubble in water.

The calculated heat transfer coefficients were related to the overall interfacial area of the bubble rather than to an estimated liquid-liquid interface. Some typical curves showing the time dependence of the transfer area A, the bubble volume V, and the weight percentage of vapor content of the bubble m are presented in Figure 3.

Instantaneous and Average Heat Transfer Coefficients

The instantaneous heat transfer coefficient U is derived from the heat balance and is given by

$$U = \frac{L\rho_v}{\Delta T} \frac{1}{A} \frac{dV}{d\theta} \tag{1}$$

The instantaneous transfer coefficient was readily obtained by graphical differentiation of plots of V as a function of θ. Since relatively low temperature differences were employed in this work, a correction for the hydrostatic head had to be introduced at each point. In general two distinct regions of the instantaneous transfer coefficients were observed (Figure 4). In the first region, associated with the initial stages of condensation, high transfer coefficients were noted, the average for many bubbles showing the transfer coefficient to be practically constant in this region. In the second region, a sharp decrease in the transfer coefficient was noted, dropping to about 10% of the average value of the first region. Whereas the changes in area and volume of tre bubbles in this second region were small but significant, the changes beyond this region fluctuated about a constant value. Within the experimental accuracy, no significant heat transfer was observed beyond the second region.

The results obtained for the two sets of different bubble diameters are summarized in Table 1* where the average transfer coefficient for the first region $\overline{U}$, as well as the corresponding vapor content at the transition between the two regions, are reported. The calculated vapor content of the bubble leaving the column is also included, the value being based on the assumption of zero liquid content in the bubble entering the column. This point will be discussed further.

Instantaneous Velocity Rise

The velocities of rise of the condensing bubbles were obtained from the height vs. time curves determined directly from the enlarged pictures. A typical velocity vs. time curve is shown in Figure 5, indicating the peculiarity of the system involved. Starting at zero velocity at the nozzle, the accelerated bubble reaches a maximum velocity corresponding to that of a gas bubble. Then, and rather abruptly, the velocity falls off, tending to the terminal velocity of a liquid drop. This phenomenon is probably associated with the partial collapse of the bubble and is closely related to the decrease, referred to above, in the instantaneous heat transfer coefficient. The relatively low-speed camera used in this study (50 to 60 frames/sec.) precluded exact measurement of the initial and collapse velocities, which are represented by dotted lines in Figure 5.

The results seen in Figure 5 differ appreciably from those obtained for evaporating drops, where the velocity increases gradually with vapor content (*1*). The results for the two velocity ranges reported in this study are in general agreement with those predicted in the literature (*11, 12*). Thus, while the velocities of all bubbles in the gaseous range were close to 30 cm./sec., the average velocity of the small bubbles in the "liquid drop" region was

* Tabular material has been deposited as document 8483 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.

about 12 cm./sec. and that of the larger ones about 14.5 cm./sec. It is interesting to note that the smaller bubbles behaved more uniformly than the larger ones. Thus, the velocity "jump" occurred consistently some 0.07 to 0.08 sec. after the bubble had been released, whereas with the larger bubbles the time of the velocity jump varied from bubble to bubble between 0.07 and 0.12 sec. after release. This nonuniform behavior of the larger drops, which sometimes even exhibited rather moderate changes in velocity, is probably associated with the larger variety of bubble shapes due to the stronger deformation of the larger bubbles. Finally, practically no effect of the temperature difference on velocity was observed in this study, although it is quite likely that the time of bubble collapse would be affected by the temperature driving force.

DISCUSSION

Characteristics of the Transfer Mechanism

The appearance of the two distinct heat transfer regions is readily understood in the light of physical observations. The first region is characterized by the turbulent behavior of the bubble, associated with deformation and oscillations. Once some 80% of the initial vapor has condensed, the bubble loses its gaseous character and behaves more or less as a liquid drop. Hence, the transition from the relatively constant high transfer rate region to that of a steeply descending one is associated with the decrease in bubble volume, with increasing liquid content, and with an appreciable decrease in the bubble velocity. By analogy to the initial stages of an evaporating drop, the internal resistance is assumed to be the rate-controlling mechanism in this second region. One would thus expect the larger bubbles to show a relatively sharper decrease in the transfer coefficients, since the transition from the turbulent to the laminar region would be more pronounced. And indeed this is what the experiment shows. The difference between the values of m_t, the vapor content at the end of the turbulent first region, and $M_{U/10}$, the vapor content at ten times lower transfer coefficient, indicates the steepness of descend of the heat transfer rate. Whereas this difference is 2 to 3% for the larger bubbles, the corresponding value for the smaller bubbles is about 10%, the higher value representing a noticeably slower descent. One may conclude that the initial diameter affects the magnitude of the transfer coefficient and that the transition between the two characteristic heat transfer ranges is dependent on the flow characteristics associated with the relative liquid content in the bubble, rather than on its absolute equivalent diameter. This is easily seen when the transfer coefficient is plotted (not shown here) against the instantaneous equivalent bubble diameter.

Some irregular patterns of the transfer rates observed in a number of runs may be of interest. The very first condensation stages exhibited different transfer rates for different bubbles. With some bubbles the initial condensation rates were appreciably higher or lower than indicated by the experimental curves in Figure 4. In all cases these initial rates dropped, or rose, very steeply to the level of the first region, similar to the one shown in Figure 4. These initial irregularities may be due to the difference in formation time, as well as to small variations in the initial degree of superheat, saturation, and liquid content

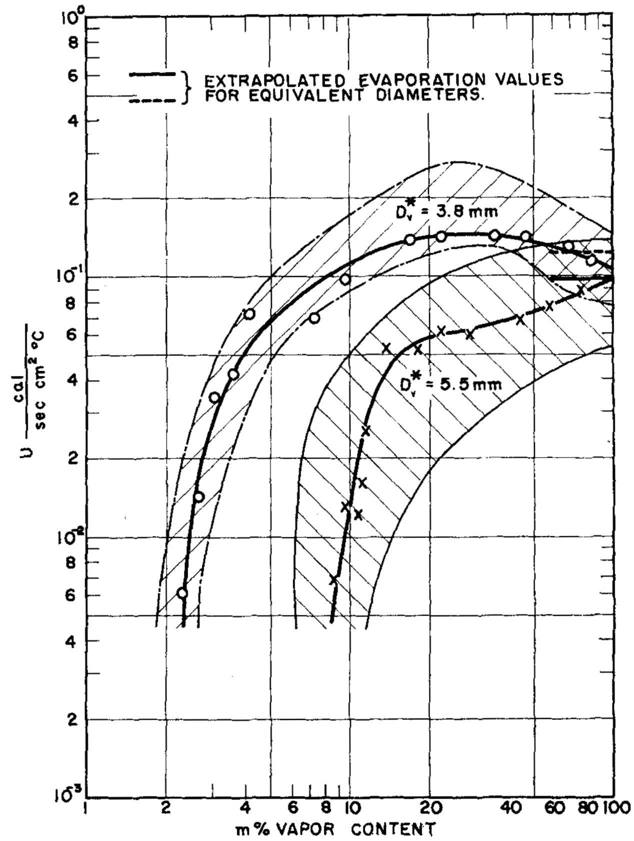

Fig. 4. Instantaneous transfer coefficients as a function of vapor content and the experimental spread. Bubbles released from orifice assumed to be liquid free. 1.0 cal./(sec.) (sq. cm.) (°C.) = 3.6 x 10^4 kcal./(hr.) (sq. meter) (°C) = 7.37 x 10^3 B.t.u./(hr.) (sq. ft.) (°F.)

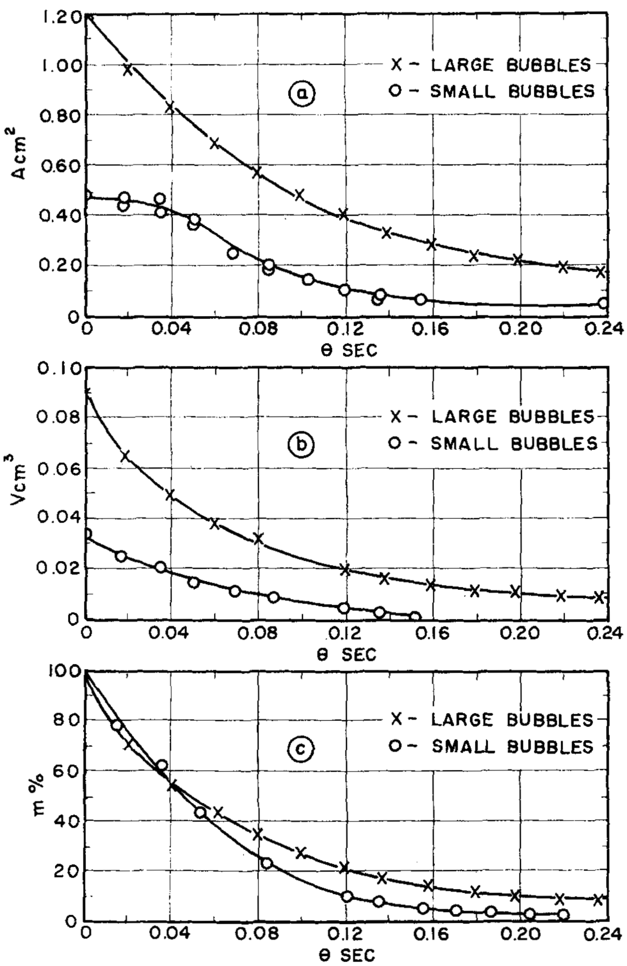

Fig. 3. Representative curves: (a) change of transfer area with time, (b) change of volume with time, (c) change of vapor content with time.

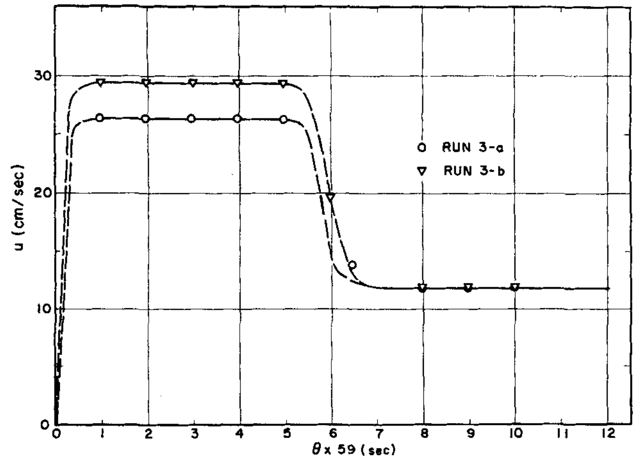

Fig. 5. Velocity of rise vs. time.

of the individual bubbles. However, since these irregularities only take place at the very beginning, their effect on the overall transfer rate is negligible.

Some bubbles also showed a peak within the first turbulent region with the transfer coefficient at its maximum some 30 to 40% higher than the characteristic level indicated by Figure 4. In these cases the integrated average heat transfer coefficient was reported as $\overline{U}$ in Table 1. Another interesting phenomenon observed in nearly 50% of all the large bubble studied concerns the appearance of a noticeable negative peak somewhere near the end of the first turbulent region, starting at about 30% vapor content and ending at about 15%, with the heat transfer coefficient at its minimum being some 30% lower than the average value of the first region. This phenomenon is most probably associated with the relative change in volume and transfer area of the bubble with time. The first stages of the turbulent region are characterized by a comparatively steady (though steep) decrease of the volume and area with time. Since both these changes are of the same magnitude, the transfer coefficients calculated by Equation (1) are almost constant. However, in these "irregular" cases of the larger bubbles, the area-volume ratio seems to increase, while the volume change with time continued to decrease, resulting in a marked decrease in the calculated transfer coefficient. After a while, however, the reduction of volume with time levels off, while the area decreases moderately, resulting in an increase of the calculated coefficient. This increase is augmented by the relatively marked decrease in temperature difference with decreasing hydrostatic head. No specific explanation for these "abnormalities" can be offered at this stage.

The effect of temperature on the transfer coefficient could not be isolated in the relatively narrow range studies (0.5° to 3°C. apparent temperature gradients). This concurs with our evaporation studies and is consistent with practically all correlations for forced convection.

Initial and Final Liquid Content in the Bubble

The initial and final bubble diameters of the larger bubbles are plotted against the apparent temperature difference, defined as the difference between the normal boiling point and the temperature of the water in the column (Figure 6). The diameter of the released bubble is apparently a function of the temperature drop, indicating that some condensation takes place during bubble formation, despite the initial superheat of up to 10°C. Moreover, condensation seems to be incomplete in the low range of temperature differences studied, with the final vapor content varying up to some 15%. This is easily understood in the light of the relatively slow transfer rates associated with internal controlling resistance of the (almost) liquid drop. However, the relative independence of the initial bubble diameter of the temperature difference above some 3°C. is rather surprising. It should be noted that the initial bubble diameter was taken as that of the bubble just detached for the nozzle, where its velocity is practically zero. Thus, one may tentatively postulate that at the higher temperature difference a liquid film forms on the periphery of the practically stagnant bubble. At this stage the transfer rate would be controlled by conduction through the liquid film and, since this stage is very short (of the order of magnitude of 0.02 sec. or less), the effect of the temperature difference will be negligible. With the smaller temperature differences, however, the liquid film (if present) is very thin, stretched, and most probably uneven, resulting in the relatively pronounced effect of the temperature gradient.

Since no effect of the initial liquid content in the bubble on the transfer rate was observed, the results reported in Table 1, as well as the related figures, have not been corrected for this effect. A correction of this type may obviously cause a slight shift of the base line in Figure 4, but would not change the general characterization of the instantaneous transfer coefficient. The calculated final vapor content of the bubbles (Table 1) may thus be considered as an approximation indicating the maximum degree of incomplete condensation. It should be noted that incomplete condensation should not cause any undue difficulties in some practical applications, as some "bleeding off" of the vapor is usually required for a secondary cycle.

Comparison with Related Work

The physical behavior of the "small" and "large" bubbles studied here closely resembles that of the first and third groups, respectively, described by Bankoff and Mason, and briefly reviewed in the Introduction. Whereas the small bubbles were smooth and ellipsoidal, the larger ones exhibited irregular shapes with relatively moderate collapse. In both cases condensation was found to be incomplete in the temperature range considered.

The transfer coefficients obtained here are lower by one order of magnitude than those reported by Bankoff. This is to be expected, considering the higher Reynolds numbers realized in his work. Moreover, one would expect the resistance to heat transfer between two phases of the same component to be appreciably lower, due to possible mass diffusion, than in the case of a two-component system.

The general characteristics of the instantaneous heat-transfer coefficients obtained in this study are in excellent agreement with those obtained in the earlier evaporation studies (*1, 2*) of single drops. Condensation-transfer coefficients were found to be higher than those of evaporation. This is most probably due to the effect of drop diameter. In general the transfer coefficient increases with decreasing liquid mass, that is, with the initial (or final) liquid drop diameter. Work is continuing on this point.

Nusselt numbers vs. Reynolds numbers are plotted in Figure 7 for typical runs of the two sizes. For comparison some curves for evaporating drops were included in Figure 8. In all these curves the Nusselt and Reynolds numbers are defined as

$$N_{Nu} = \frac{UD_e}{k_o} \text{ and } N_{Re} = \frac{D_e u \rho_o}{\mu_o}$$

where the instantaneous heat transfer coefficient is related to the overall bubble-water interface. As seen in Figure 8, the curves fall in the same range of the Nusselt number, with the Reynolds numbers increasing with initial (or final) liquid drop diameter. This is consistent with the practical independence of the velocity of rise on the bubble diameter. The particular characteristic of the smallest bubble, which exhibits an almost constant Nusselt number over a relatively wide range of Reynolds numbers, is still evident in the larger condensing bubbles but disappears in the evaporating drops. Although no complete explanation of this fact is available so far, this phenomenon may be associated with the peculiar velocity characteristics of the small condensing bubbles (Figure 5). As the transition jump in the velocities of the larger bubbles is much more moderate, the constant Nusselt number region for these bubbles may, as is indeed the case, be much smaller. As is to be expected, the larger evaporating drops, whose velocity increases moderately with vapor content, exhibit no such "plateauing."

Except for the effect of the drop diameter, the heat transfer mechanism of condensation and evaporation of one component in immiscible medium seem to be very much the same. This is evident from the general similarity of the flow characteristics of the bubbles, as well as from Figure 8, where some of the experimental data of condensing bubbles and evaporating drops are compared. It should be borne in mind that the experimental heat transfer coefficient in this work is related to the entire area of the bubble, whereas [and as established earlier (*1*, *2*)], the transfer takes place mainly through the liquid-liquid interface.

The maximum overall transfer coefficient is given by

$$N_{Nu} = 0.27\ (N_{Re} N_{Pr})^{1/2} \qquad (2)$$

Equation (2) was derived (*1*) by assuming a liquid-phase concentration at the bottom of a spherical drop at

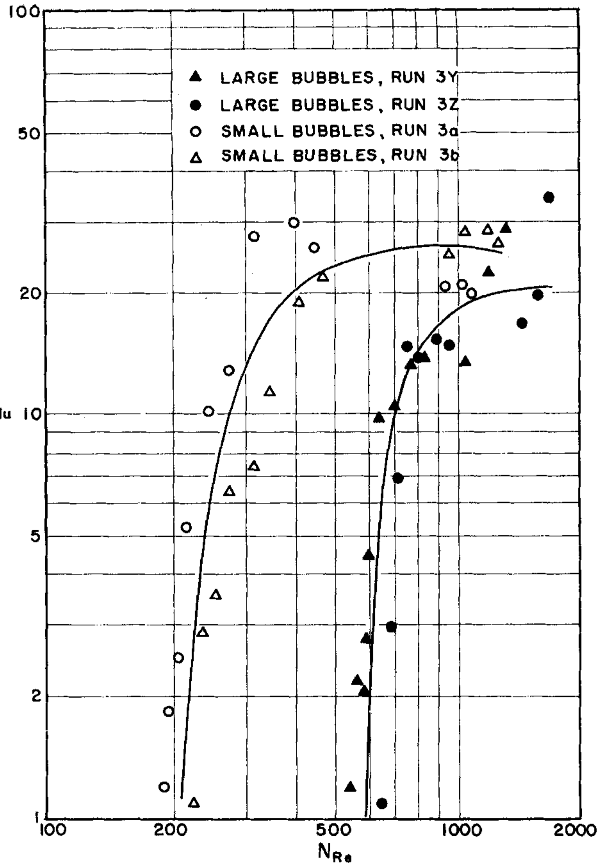

Fig. 7. Nusselt vs. Reynolds number for condensing bubbles.

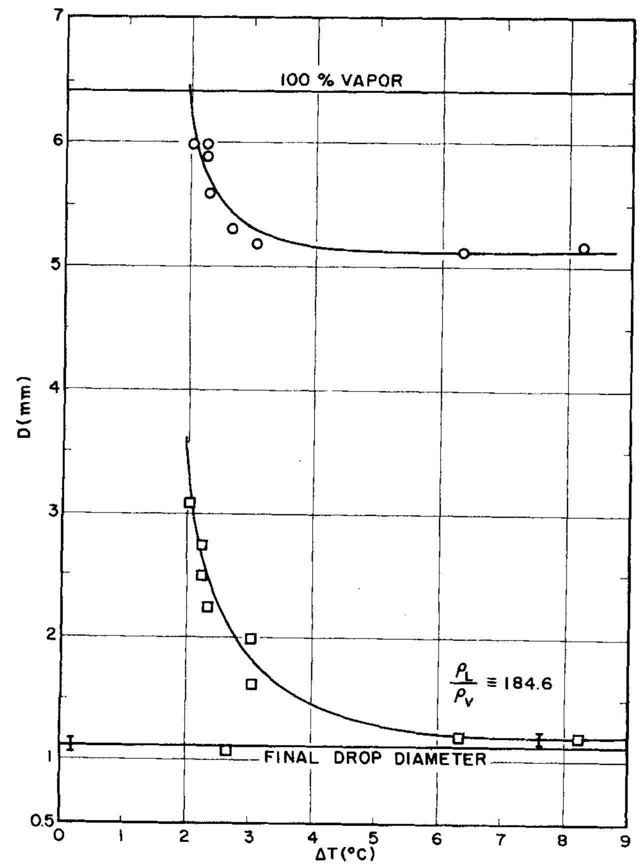

Fig. 6. Dependency of initial and final bubble diameter on the temperature difference. Nozzle diameter 6 mm.

a constant (90 deg.) opening angle. Agreement with the experiment data is evident.

The effect of the presence of inert gas in the vapor phase on the heat transfer rates in this system has not been studied to date. However, Hasson's (*13*) studies of condensation heat transfer between steam and a free falling sheet of water, as well as Grassmann's (*9*) work on heat transfer between steam bubbles and water, proved that the presence of inert gases appreciably reduced the transfer coefficients. One would expect similar reduction in the present case.

CONCLUSIONS

The study of condensation of vapor bubbles rising in an immiscible liquid medium sheds some light on the transfer characteristics of this mode of heat transfer. These are generally similar to those found earlier in the complementary study of evaporating drops, indicating that here, too, most of the heat transfer takes place at the liquid-liquid interface.

Two distinct regions of the transport rate were observed. The first and largest (up to 80% liquid content), is the so-called "turbulent" region, associated with appreciable bubble deformations and oscillations. In the second, the so-called "laminar" region, the transfer rate decreases appreciably with the bubble becoming mainly a liquid sphere with high internal resistance to transfer.

The two bubble sizes (3.8 and 5.5 mm. initial diameter) studied here showed the transfer coefficients to be higher for that smaller bubbles. These results are in accord with the evaporation data. The higher transfer coefficients realized in the condensation studies are most probably due to the smaller diameters (or masses) of the condensing bubbles. A study of the effect of diameter on the

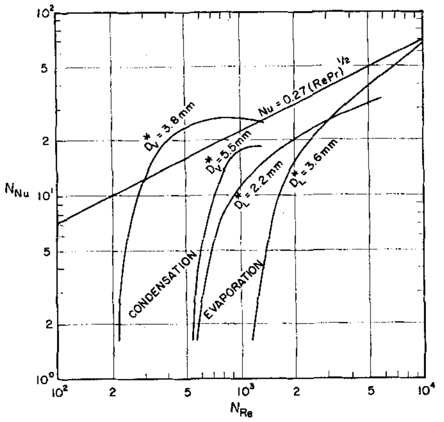

Fig. 8. Nusselt vs. Reynolds number. Comparison with evaporation data of single drops (*1*).

transfer coefficient is in progress. Evaluation of the present data indicates that the same relationships apply to condensing bubbles and to evaporating drops. Thus, the data presented here may be considered as an extension of the evaporation heat transfer studies (*1*) with the total presently available data ranging between, approximately, 0.6 to 4 mm. *liquid* drop diameter.

The study presented here does not account for the condensation which may be expected to take place during the bubble-formation period. Although superheated (10°C.) vapors were used in this study, some condensation did take place during bubble formation. Since the effect of the conditions of the (initial) released bubble on the general heat transfer characteristics were rather small, the data were presented under the assumption of zero liquid content in the initial bubble. A correction for the initial liquid content, if and when available, should only cause a shift in the abscissa, with little, if any, change in the form of the curves. It should be noted that this study of single condensing bubbles is actually the limiting case for practical applications where trains of high-frequency bubbles would be introduced. In that case, bubble-formation period and, hence, condensation, would be smaller. This is substantiated by the recent condensation studies of Harriott and Wiegandt (*7*) who noted that under favorable flow conditions entrance effects were not important.

This study also demonstrates that at the range of practical interest of low driving forces (up to 3°C.) condensation is not spontaneous and, moreover, not even complete. No distinction between the vapor and (volatile) liquid phases in the condensing bubble could be observed even at the last stages of this process in the low range of temperature differences. However, the phases were easily distinguishable at high temperature differences (25°C.).

The results compare favorably with data for condensation in a two-phase, single-component (steam-water) system. However, values smaller by one order of magnitude were obtained for the three-phase, two-component (isopentane-water) system, mostly due to the lower turbulence of our system compared with the former.

In agreement with the evaporation studies, no significant effect of the temperature differences on the transfer coefficient was observed in the narrow range studied. However, temperature did seem to affect the initial and final liquid contents in the bubble.

ACKNOWLEDGMENT

The financial support of the Israel National Council for Research and Development is gratefully acknowledged. The authors also wish to express their thanks to R. Abed and J. Shahashua for their devoted help in the experimental part of this work.

NOTATION

A = instantaneous overall interfacial transfer area
C_p = heat capacity
D = diameter, instantaneous
D^* = diameter, initial
D_e = equivalent, volumetric spherical, diameter
H = height of water seal
h = heat transfer coefficient
k = thermal conductivity
L = latent heat
m = weight percent vapor content
N_{Nu} = Nusselt number
N_{Pr} = Prandtl number
N_{Re} = Reynolds number
R = radius
T = temperature
T_B = boiling point temperature
U = overall heat transfer coefficient, instantaneous value
$\bar{U}$ = average overall transfer coefficient for turbulent region
u = velocity of rise
V = bubble volume

Greek Letters

θ = time
μ = viscosity
ρ = density
σ = surface tension

Subscripts

i = internal
o = external, continuous phase
L = liquid
v = vapor
I = end of turbulent region
II = end of calculation
III = end of experimental data
$\bar{U}/10$ = at 10% of the average overall transfer coefficient of first region

LITERATURE CITED

1. Sideman, Samuel, and Yehuda Taitel, *Intern. J. Heat Mass Transfer,* **7,** 1273 (1964).
2. Sideman, Samuel, and Gideon Hirsch, *Israel J. Technol.,* **2,** 237 (1964).
3. Wiegandt, H. F., *Office Saline Water Progr. Rept. No. 41* (August, 1960).
4. Wilke, C. R., C. T. Cheng, V. L. Ledesma, and J. W. Porter, Sea Water Conversion Lab. Univ. California, Berkeley Rept. No. 63-6, (August, 1963); *Chem. Eng. Progr.,* **59,** No. 12, 69 (1963).
5. Lackey, D. L., M.Sc. thesis, Univ. California, Berkeley (1961).
6. Hu, S., *The Refining Engineer,* **C-12,** 722 (1956).
7. Harriott, Peter, and H. F. Wiegandt, *A.I.Ch.E. J.,* **10,** No. 5, 755 (1964).
8. Bankoff, S. G., and J. P. Mason, *ibid.,* **8,** No. 1, 39 (1962).
9. Grassman, P., and E. Wyss, *Chem. Eng. Tech.,* **34,** No. 11, 755 (1962).
10. Sideman, Samuel, *Chem. Eng. Sci.,* **19,** No. 6, 426 (1964).
11. Levich, V. G., "Physicochemical Hydrodynamics," p. 451, Prentice-Hall, Englewood Cliffs, N. J. (1962).
12. Harmathy, T. Z., *A.I.Ch.E. J.,* **6,** No. 2, 281 (1960).
13. Hasson, David, Dan Luss, and Uri Navon, *Intern. J. Heat Mass Transfer,* **7,** 983 (1964).

Manuscript received July 16, 1964; revision received December 8, 1964; paper accepted May 21, 1965. Paper presented at A.I.Ch.E. Minneapolis meeting