Film Boiling of Helium I and Other Liquefied Gases on Single Wires

T. H. K. FREDERKING

Institut für Kalorische Apparate und Kältetechnik, Swiss Federal Institute of Technology, Zurich, Switzerland

Heat transfer coefficients have been obtained for natural-convection film boiling of helium I on single wires with a diameter ranging from 5 to 50 μ. The measurements covered temperature differences of 30° to 1,000 °K. between the heating surface and the saturated liquid under atmospheric pressure. The results are correlated in dimensionless form (Nusselt number vs. the product of the Grashof and Prandtl numbers) and compared with data for nitrogen and measurements of other investigators on film boiling of liquefied gases.

In recent years technical developments where large quantities of heat are transferred across comparatively small areas have increased the interest in all types of heat transfer at high flux densities and have focused attention on boiling.

In continuation of previous studies in the nucleate boiling region (*1*) measurements were made on stable film boiling of helium I under atmospheric pressure. There are some advantages in the use of helium I as a test liquid: its low boiling point permits a wide range of temperature differences without appreciable radiation influence and it has a well-known simple structure and does not attack the heating surface, although the low heat of vaporization necessitates a small heating device in order to keep the amount of vaporized gas within tolerable limits.

APPARATUS EMPLOYED

Electrically heated platinum wires were soft-soldered to copper current and potential leads. For the smaller units Wollaston wires were used. To reduce the chance of breakage the silver layer was etched off after soldering. The diameters were determined by microscope, measurements being made with both horizontally and vertically mounted wires. All experiments were carried out in a Dewar vessel of 6 cm. I. D. The tests were conducted by gradually increasing the current until stable film boiling was reached. By varying the power input and measuring the current and potential drop, one obtained the stable film-boiling curve. The average temperature of the test section was determined by resistance thermometry. The resistance-temperature characteristic was obtained from resistance measurements at the ice point and at liquid helium temperature, with the validity of Matthiessen's rule assumed and the data for pure platinum in the standard reference works (*2*) used. In most cases the power was increased until the wire burned out.

RESULTS OBTAINED

Table 1* gives a sample of the measured data for a single wire and the calculations made to obtain the heat transfer coefficient. In Figure 1 the experimental results for horizontal wires are presented as a plot of the average heat transfer coefficient, defined by the equation $q/A = h\ \Delta T$. (W = watt; 1 W/(°K.)(sq. cm.) = 1,761 B.t.u./(hr.)(sq. ft./°F.); 1 W/(°K.)(sq. cm.) = 8,600 kcal./(°K.)(sq. m./hr.).

At the highest temperature reached one obtains the order of magnitude of the film thickness by calculating $B = k/h$ (k at average film temperature), which yields B of about two times the wire diameter. The temperature gradients within the film reach values of the order of magnitude of 10^5 °K./cm. The mean free path of the gas molecules changes considerably across the film [from about (30 to 6,000) 10^{-8} cm.], causing changes in the transport properties for momentum and heat. At the burnout point current densities up to 5×10^5 A/sq. cm. were reached.

The heat transfer coefficients for some vertically mounted wires show no great differences compared with those for horizontal ones, the maximum observed difference being about 15% less for the vertical wires. (The lengths used were 3.60 cm. for 30-μ nominal diameter, 3.07 cm. for 10-μ wire, and 0.625 cm. for 5-μ wire.) The effect of wire length on h is very weak, as was observed in additional measurements with wires of 15-μ nominal diameter. Within the range of lengths from 3 to 10 cm. only a slight increase of h with increasing length was found; however it is difficult to give an exact quantitative relationship because scattering of data in these measurements is inevitable. A vertical cylinder is defined by two linear dimensions, the diameter and length. (Only for very short horizontal cylinders are end effects noticeable.) Generally it is to be expected that the influence of the ratio of length to diameter will not be the same at very small and very large diameters. A further complication comes from the existence of a laminar- and turbulent-flow region. (For long vertical cylinders the mean heat transfer coefficient is nearly unaffected by the mean h value of the relatively short viscous-flow path.) Thus for all diameters the h values on vertical cylinders will not be superior to those on horizontal ones, as was found by Hsu and Westwater (*8*) in film boiling on vertical tubes with $\frac{3}{8}$ to $\frac{3}{4}$ in. O.D. (9.5 to 19 mm.). A better knowledge of the critical Reynolds number of the film and the turbulent heat transfer would give a better explanation of the vertical film-boiling heat removal.

In addition to the helium measurements some experiments were conducted with nitrogen. In Figure 2 the heat transfer coefficients for thin horizontal wires measured by the author and by other authors (*3*, *4*) are presented. The shape of the nitrogen curve is similar to that obtained for oxygen (*5*). Beyond the heat-flux minimum (Leidenfrost point) h gradually decreases with increasing temperature difference toward a flat minimum. At higher temperatures of the heating surface the shape of the curve becomes steeper and steeper with increasing radiation. Compared with the helium data, the temperature range between the minimum of h and the beginning of radiation is considerably smaller.

THEORETICAL ANALYSIS

A theoretical solution of film-boiling heat transfer was given by Bromley (*3*), who treated the problem in analogy to the film-condensation theory of Nusselt. He has shown that the mean coefficient of heat transfer without radiation influence for the film boiling on horizontal cylinders is given by

$$h = 0.62 \cdot \left[\frac{k^3 \rho(\rho_L - \rho) g \lambda'}{D \mu\ \Delta T} \right]^{\frac{1}{4}} \qquad (1)$$

*Tabular material has been deposited as document No. 5972 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.

TABLE 1. SAMPLE OF MEASURED DATA AND CALCULATION OF THE HEAT TRANSFER COEFFICIENT

Wire, F 52
Diameter, $D = 5.5\,\mu$
Length, $L = 0.537$ cm.
Surface area, $A = 9.28 \cdot 10^{-4}$ sq. cm.
Ice-point resistance, R_{273} 25.8 ohms
Resistance at liquid helium temperature, $R_{4.2}$ 0.61 ohm

Measured data power Amperes	Volts	Watts	Heat flux density watts/sq. cm.	Wire resistance, ohms	Resistance function $\frac{R - R_{4.2}}{R_{273} - R_{4.2}}$	Wire temperature* (absolute), °K.	Temperature difference, °K.	Heat transfer coefficient h, watts/(sq. cm.)(°K.)
0.0906	0.680	0.0616	66.4	7.50	0.274	97.4	93.2	0.711
0.0892	0.900	0.0803	86.4	10.1	0.376	121	117	0.739
0.0898	1.09	0.0979	105.5	12.1	0.456	140	136	0.776
0.0915	1.28	0.117	126	14.0	0.531	158	154	0.818
0.0911	1.46	0.133	143	16.0	0.611	176	172	0.831
0.0917	1.65	0.151	163	18.0	0.690	198	194	0.840
0.0923	1.95	0.181	194	21.1	0.815	227	223	0.869
0.0941	2.20	0.207	223	23.4	0.905	250	246	0.906
0.0965	2.67	0.258	278	27.6	1.07	291	287	0.969
0.0964	3.02	0.292	315	31.3	1.22	330	326	0.966
0.0972	3.54	0.344	371	36.4	1.42	380	376	0.986
0.0989	4.05	0.400	431	41.0	1.60	428	424	1.02

*Taken from standard tables (2).

The physical properties of the vapor are taken at the average temperature of the film. The effective latent heat of vaporization was taken in first approximation as $\lambda_1' = \lambda + 0.5\, c_p \cdot \Delta T$. A later (*6*) derived effective enthalpy difference $\lambda_2' = \lambda \cdot [1 + 0.4\, c_p\, \Delta T/\lambda]^2$ gives a better fit with observed data. Apart from the effect of diameter the boiling heat transfer can be described fairly well by Equation (1), which has been derived under the assumption of negligible film thickness in comparison with the diameter. Bromley's experimental results on cylinders 0.19 to 0.47 in. (4.8 to 12 mm.) O.D. are in good agreement with the theoretical prediction that h should be proportional to $D^{-1/4}$. For thin wires, however, the assumption of negligible film thickness is not valid. Measurements on boiling oxygen by Banchero, Barker, and Boll (*5*) gave heat transfer coefficients which were some 10% higher than those calculated by the Bromley equation for the smallest diameter used (0.025 in., or 0.0635 mm.). The data for the present tests on helium are up to 3.5 times larger for the thinnest wire than the theoretical values obtained by the insertion of λ_2' in Equation (1). In the diameter range used here [(5 to 50) $\times 10^{-3}$ mm.] h is proportional $D^{-0.7}$.

Vapor-layer Formation

In natural-convection film boiling at an inclined heating surface a continuous vapor film is flowing from the lower edge upward along the surface under the action of the gravity field, in contrast to the nucleate boiling mechanism. The driving temperature difference between the heating surface and the saturated liquid must exceed a certain value in order to establish a stable flow pattern. For the derivation of Equation (1) it is essential that the vapor film be sufficiently thin. Under this assumption the increase in thickness due to evaporation at the phase boundary corresponds immediately to the heat supply from the heating surface. In first approximation the temperature profile of the laminar flowing vapor is linear; the superheat and the heat capacity of the vapor are taken into account by the insertion of λ_2' instead of λ into Equation (1). In accordance with the equation the increase in film thickness for a given heat input, other variables being unchanged, is higher the lower the heat of vaporization. Other factors which are important for nucleation, such as surface roughness, do not enter the theory. Its important variables are the physical properties of the vapor within the film. Considering the good agreement with the experiments in the range of moderate diameters one may conclude that the rate-controlling mechanism must be the transfer of heat across the vapor film.

Natural-Convection Mechanism

Since the vapor resistance is controlling, there is some analogy to natural convection of a horizontal cylinder by a gas without boiling if other phenomena caused by the presence of the denser phase are neglected. This becomes evident for the limiting case of a liquid boiling under a pressure approaching the critical (vanishing latent heat of vaporization, vanishing phase boundary). Within the film the vapor is rising under the action of buoyant and viscous forces. The motion of the vapor is caused by gravitation in association with the density variations which occur as a result of the temperature difference produced by the heat-dissipating cylinder. Consequently the dimensionless groups $N_{Nu} = hD/k$ and the product of $N_{Gr} = D^3\rho^2\beta g\, \Delta T/\mu^2$ and $N_{Pr} = c_p\mu/k$, governing the natural-convection heat transfer without boiling, have been used to correlate the film-boiling data in dimensionless form. All physical properties are taken at the arithmetic mean temperature; in this sense $\beta = 1/T_m$.

The range of applicability of this correlation may be seen when one rewrites Equation (1) in dimensionless form for a liquid with negligibly low latent heat of vaporization ($\lambda \ll 0.5\, c_p\, \Delta T$) and

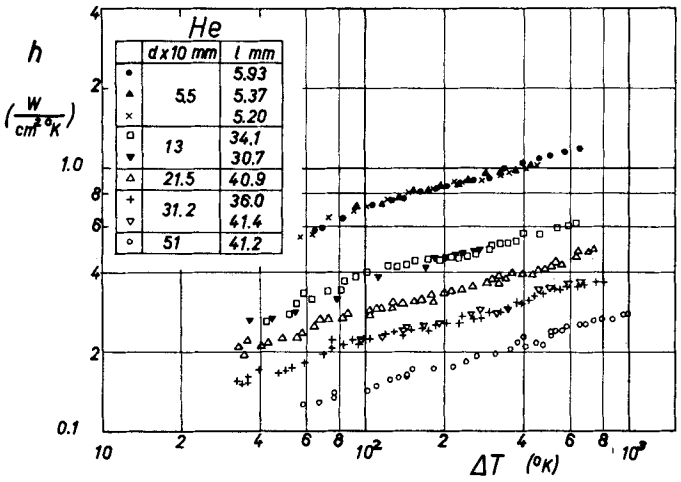

Fig. 1. Heat transfer coefficient for film boiling of helium on horizontal thin wires under atmospheric pressure.

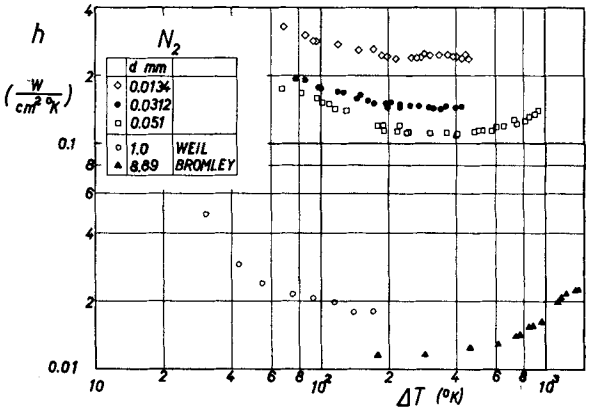

Fig. 2. Heat transfer coefficient for film boiling of nitrogen on horizontal wires and tubes under atmospheric pressure.

uses the approximate expression λ_1'. The Bromley equation can be written

$$N_{Nu} = 0.62\left[\frac{D^3\rho(\rho_L - \rho)g\lambda'}{k\mu\ \Delta T}\right]^{\frac{1}{4}} \quad (2)$$

and approximately with $\lambda' \approx 0.5\ c_p\ \Delta T$

$$N_{Nu} \approx C_1\left[\frac{D^3\rho(\rho_L - \rho)g}{\mu^2}\ \frac{\mu c_p}{k}\right]^{\frac{1}{4}} \quad (3)$$

By definition the coefficient of thermal expansion is $\beta = -(1/\rho)(\partial\rho/\partial T)$. For purposes of comparison one takes a modified coefficient $\beta^* = (1/\rho)[(\rho_v - \rho)/\Delta T]$. Thus $N_{Gr}{}^* = D^3g\ \Delta T\rho^2\beta^*/\mu^2 = D^3\rho g(\rho_v - \rho)/\mu^2$, and the approximate form of the Bromley equation for negligibly low λ becomes

$$N_{Nu} \approx C_1(N_{Gr}{}^*N_{Pr})^{\frac{1}{4}}\cdot\left[\frac{\rho_L - \rho}{\rho_v - \rho}\right]^{\frac{1}{4}} \quad (3a)$$

The last factor on the right side approaches unity near the critical pressure, where $\rho_v = \rho_L$. Equation (3a) in terms of the argument $N_{Gr}N_{Pr}$ used in this correlation becomes

$$N_{Nu} \approx C_1(N_{Gr}N_{Pr})^{\frac{1}{4}} \cdot\left[\frac{\beta^*}{\beta}\ \frac{\rho_L - \rho}{\rho_v - \rho}\right]^{\frac{1}{4}} \quad (3b)$$

with

$$\frac{\beta^*}{\beta}\cdot\frac{\rho_L - \rho}{\rho_v - \rho} = \frac{\rho_L - \rho}{\rho}\cdot\frac{T_m}{\Delta T}$$

$\beta = 1/T_m$ being used. For helium with its low boiling point (4.2°K. under atmospheric pressure) at sufficiently high temperatures with $\Delta T/T_m \approx 2$ and $\rho \ll \rho_L$

$$N_{Nu} \approx C_1(N_{Gr}N_{Pr})^{\frac{1}{4}}\cdot\left(\frac{1}{2}\cdot\frac{\rho_L}{\rho}\right)^{\frac{1}{4}} \quad (3c)$$

In Figure 3 a plot of N_{Nu} vs. $N_{Gr}N_{Pr}$ is presented for helium and nitrogen data and for published data on other liquefied gases boiling under atmospheric pressure. The experimental results for stable film boiling of helium can be represented by

$$N_{Nu} = C_2(N_{Gr}N_{Pr})^m \quad (4)$$

with $C_2 = 2.5$ and $m = 0.11$ for the range of variables $10^{-7} < N_{Gr}N_{Pr} < 10^{-1}$. The thin-wire nitrogen data can be approximated by a similar relation with a somewhat greater constant. Known film-boiling results for oxygen (*5*), nitrogen (*3*, *4*), and hydrogen (*4*) with larger diameters are added covering $N_{Gr}N_{Pr}$ values larger than unity. (The plotted nitrogen data of Bromley are the corrected values excluding the influence of radiation.)

Effect of Diameter

A general trend of the data is observable similar to the well-known curve for natural-convection cooling on horizontal cylinders without boiling (*7*). At low valuse of $N_{Gr}N_{Pr}$ the Nu values increase with an increase of $N_{Gr}N_{Pr}$ at a very slow rate. For values of the argument greater than unity this rate increases until N_{Nu} becomes proportional to $(N_{Gr}N_{Pr})^{1/4}$. In this region h is proportional to $D^{-1/4}$, as predicted by Bromley's equation. If the heat transfer coefficient is proportional to D^{-n}, then from Equation (4) this exponent becomes $n = (1 - 3m.)$. In this way the dimensionless correlation permits an estimate of the influence of diameter on the heat transfer coefficient without radiation.

For the greatest diameter used by Banchero (0.750 in. or 19.05 mm.) deviations of the h values calculated by the Bromley equation were also observed. In the dimensionless correlation of these data m approaches $\frac{1}{3}$, and h is nearly independent of the diameter. In natural convection without boiling this means turbulent flow. As for this diameter, no detailed observations regarding turbulence were made, and the exact value of m cannot be taken from this single run; conclusions on the transition laminar-turbulent are not possible, and the data were omitted in Figure 3.

One may note that in general for any given diameter of the cylinder an extension of the boiling curve to either lower or higher ΔT, corresponding to higher or lower values of $N_{Gr}N_{Pr}$, would lead to values of N_{Nu} lying above the general curve shown. At the higher $N_{Gr}N_{Pr}$ this occurs because the curve is continued into the transition region; at the lower values of the same dimensionless number the N_{Nu} values, calculated with the total heat transfer coefficient including radiation, increase toward the burn-out point. The presented points in this way have the character of a lower limit for the heat transfer coefficient.

Effect of Fluid

For the case of heat transfer by convection without phase change the Nusselt numbers are known to be entirely independent of the nature of the gas. It is not surprising, however, that in the case presented here there should be differences in the N_{Nu} values for different gases because the heat transfer process in film boiling is much more complicated than that without phase change. Of all gases investigated helium shows the greatest similarity in Nusselt numbers for film boiling and natural-convection cooling. This becomes understandable from its very low heat of vaporization [under atmospheric pressure about 20 joules/g. and c_p about 5 joules/(g.)(°K.)] [1 joule/g. = 0.431 B.t.u./lb.] and a ratio of pressure to critical pressure of about 44% at 1 atm. For nitrogen and oxygen this ratio is considerably smaller (about 3 and 2% respectively), and the latent heat of vaporization is about ten times larger than for helium. The curves for oxygen and nitrogen in Figure 3 at low temperature differences already show small deviations due to the influence of the latent heat of vaporization. [For the range of higher $N_{Gr}N_{Pr}$ a smooth curve for oxygen is obtained when one multiplies N_{Nu} with the correcting factor $[\lambda/(c_p\ \Delta T) + 0.5]^{-1/4}$ or $[\lambda/(c_p\ \Delta T)\cdot(1 + 0.4\ c_p\ \Delta T/\lambda)^2]^{-1/4}$ according to Equation (1).] When one considers the complicated conditions caused by the presence of the denser liquid separated from the gas by a more or less irregularly shaped phase boundary, the variation of vapor flow due to vaporization along this boundary, and the bubble-discharge mechanism and notices the various pressure-ratio values, the differences in the N_{Nu} numbers for the various liquefied gases are remarkably small. In general, the author's results show that great similarity exists in the behavior of these gases at the same film Reynolds number.

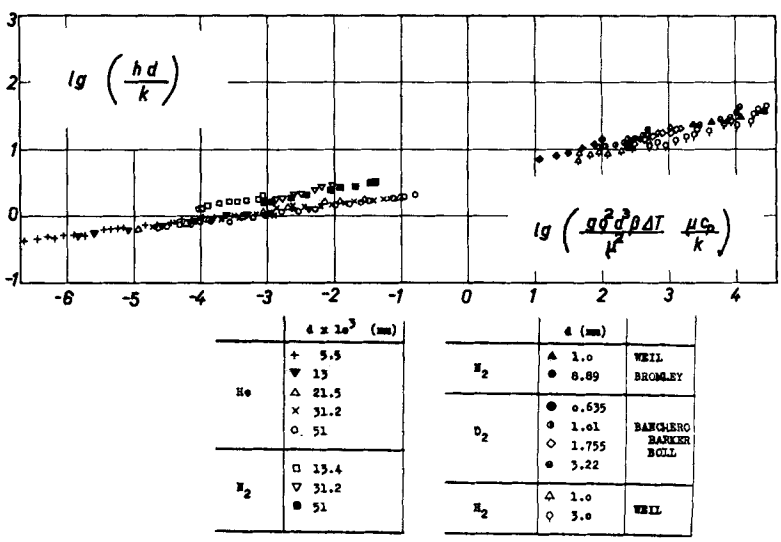

Fig. 3. The Nusselt number as a function of the product of the Grashof and Prandtl numbers for film boiling on horizontal cylinders under atmospheric pressure.

ACKNOWLEDGMENT

The work was supported by the schweizerischen Nationalfonds. Thanks are due to Professor P. P. Grassmann and Dr. J. L. Olsen for helpful discussions and support in the preparation of this paper.

NOTATION

A = area of heating surface
B = film thickness
C_1 = numerical constant
C_2 = numerical constant
c_p = specific heat at constant pressure
D = diameter ($d = D$ in figures)
g = acceleration due to gravity
h = mean heat transfer coefficient, 1 W./(°K.)(sq. cm.) = 1,761 B.t.u./(sq. ft.)(hr./°F.)
k = heat conductivity of vapor
L = length of test section ($l = L$ in figures)
m = exponent of empirical correlation
n = empirical exponent
$N_{Gr} = D^3 \cdot \rho^2 \beta g \, \Delta T/\mu^2$

$$N_{Gr}^* = \frac{D^3 g \rho(\rho_v - \rho)}{\mu^2}$$

modified Grashof number
$N_{Nu} = hD/k$
$N_{Pr} = c_p\mu/k$
q = rate of heat flow
R = electrical resistance
R_{273} = electrical resistance at ice point
$R_{4.2}$ = electrical resistance at liquid-helium temperature
T = absolute temperature
T_m = mean temperature of vapor
ΔT = temperature difference

Greek Letters

β = Coefficient of thermal expansion
β^* = Modified coefficient of thermal expansion
ρ = density of vapor
ρ_L = density of saturated liquid
ρ_v = density of saturated vapor
μ = viscosity of vapor
λ = latent heat of vaporization
λ' = effective heat of vaporization

LITERATURE CITED

1. Karagounis, Aristides, *Suppl. Bull. de l'Institut International du Froid*, Annex 2, 195 (1956).
2. "American Institute of Physics Handbook," pp. 4–13 (1957); "Handbook of Chemistry and Physics," 34 ed., p. 2190 (1952–1953); G. K. White, and S. B. Woods, *Rev. Sci. Instr.*, **28**, 640 (1957).
3. Bromley, L. A., *Chem. Eng. Progr.*, **46**, 211 (1950).
4. Weil, Louis, "IVe Congr. Intern. du Chauf. Industr. Paris," No. 210 (1952).
5. Banchero, J. T., G. E. Barker, and R. H. Boll, *Chem. Eng. Progr. Symposium Ser. No. 17*, **51**, p. 21 (1955).
6. Bromley, L. A., *Ind. Eng. Chem.*, **44**, 2966 (1952).
7. Jakob, Max, "Heat Transfer," vol. I, John Wiley, New York (1949); Hermann Senftleben, *Z. angew. Phys.*, **3**, 361 (1951).
8. Hsu, Y. Y., and J. M. Westwater, *A.I.Ch.E. Journal*, **4**, 58 (1958).

Manuscript received September 11, 1958; revision received December 8, 1958; paper accepted December 29, 1958.

COMMUNICATIONS TO THE EDITOR

The Uselessness of Raffinate Reflux

J. F. WEHNER

The Catholic University of America, Washington, D. C.

The theory behind the separation of liquid mixtures into their constituents by solvent extraction is based on the relatively simple, exact, material-balance calculation which may be done graphically for a two-component system. In this operation a feed stream is separated into two streams by contact with a partially miscible solvent in a countercurrent cascade (*1*, *2*). Ideally one component is extracted into a solvent rich phase and the other is obtained in a solvent poor or raffinate phase. The separation is complete when the solvent is recovered from each stream. In a finite cascade each constituent is contaminated by a certain portion of the other constituent, which can be made as small as desired if the solvent is partially miscible with each component. Even so, to achieve this degree of separation the cascade must be modified by feeding into an intermediate stage and refluxing a portion of the product recovered from the extract.

A number of expositions of this theory show a countercurrent cascade which also includes reflux from the raffinate phase as a useful method of operation. This mode of operation is a needless generalization of the reflux concept, as it cannot achieve any degree of separation which cannot be obtained in its absence. The number of theoretical stages required for a desired separation is the same with or without raffinate reflux. In addition the use of raffinate reflux requires an extra solvent mixing stage. The saturation of the solvent that is achieved in this mixing stage can in no way aid the possible degree of separation. That the number of theoretical stages other than the mixing stage depends only on the degree of separation and an extract reflux ratio great enough to avoid a pinch point at any stage along the cascade is shown by locating the operating points and stepping off stages starting from the raffinate end. Alternately it can be seen that the number of stages is exactly the same when the material balances are started from the extract end and the reflux ratio is adjusted by trial and error until an integral number of stages is achieved. This latter condition is in reality the only situation in which the solution is exact mathematically. The nonintegral number of stages generally obtained for an arbitrary reflux ratio is only an approximation.

The lack of usefulness of raffinate reflux applies also in the case of extraction with a solvent that is immiscible with only one of the constituents of a binary system. In this case extract reflux may or may not be used. Without extract reflux, raffinate reflux achieves with an extra mixing stage only that separation which an adequate solvent-to-feed ratio already assures. Extract reflux can improve the degree of separation by a considerable amount if a solvent of low selectivity must be used but will not greatly aid the separation if a highly selective solvent is available.

ACKNOWLEDGMENT

The author is grateful to Professor M. R. Fenske for his constructive review.

LITERATURE CITED

1. Treybal, R. E., "Liquid Extraction," McGraw-Hill, New York (1951).
2. Perry, John H., ed., "Chemical Engineers' Handbook," 3 ed., p. 713 (1950).