The Evaporation of Carbon Tetrachloride in a Wetted-Wall Column

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The wetted-wall column, a simple construction of known wetted area, has frequently been used to test theories of mass transfer. Gilliland and Sherwood (*1*) were among the first to evaporate solvents into an air stream in a wetted-wall column. They showed that for this case of gas film control, mass transfer coefficients for different solvents could be correlated by the gas Reynolds and Schmidt numbers. A good analogy with heat transfer was found. Liquid rate was not considered to influence the gas film coefficient.

Recently, Kafesjian et al. (*3*), after reviewing some work on the effect of liquid rate on gas pressure drop in wetted-wall columns (*2, 5*), studied the effect of liquid rate on the rate of evaporation of water. They correlated their results and those of other workers by

$$N_{Sh} \frac{p_{BM}}{p} = 0.0065\, N_{Re_g}^{0.83}\, N_{Re_l}^{0.15} \quad (1)$$

This equation applied only to the evaporation of water in a 1-in. diameter wetted-wall column. The effect of liquid rate was attributed partly to the liquid surface velocity relative to that of the gas effectively increasing the gas Reynolds number (*2, 4*) and partly to the effect of ripples on the liquid surface.

Very little is known of the effect of liquid rate on gas film mass transfer coefficients for solvents other than water. McCarter and Stutzman (*4*) used a 3-in. diameter column and found that the effect of liquid rate could be explained by means of the relative velocity effect only.

In the work presented below, carbon tetrachloride was evaporated into an air stream in a 1-in. diameter wetted-wall column. Liquid rate, gas rate, and temperature were varied, and the amount of evaporation was measured directly by solvent loss.

APPARATUS

The apparatus used was similar to that of other workers. Air from a centrifugal fan was passed countercurrent to carbon tetrachloride falling in a liquid film down the inside of a vertical tube. The carbon tetrachloride was recycled by a pump through a small glass sump tank maintained at a constant temperature by electric heaters and a thermostat. The rate of evaporation was measured directly by the change in level of the liquid surface in a constant head burette, fitted with an air bleed as in a Marriott bottle, which acted to maintain a constant amount of carbon tetrachloride in the liquid circuit.

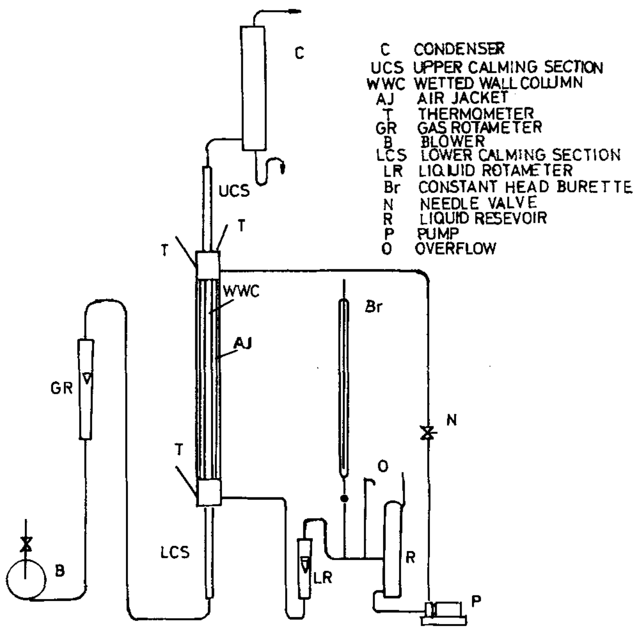

Fig. 1. Flow sheet of apparatus.

A flow sheet of the apparatus is shown in Figure 1.

The wetted-wall column consisted of a vertical brass pipe 1 in. I.D. and 24 in. long. Gas-calming sections were provided; the entry calming section was 30 in. long and the exit calming section 14 in. long. The column was set vertically by plumb bob, and the calming sections were carefully aligned with the mass transfer section.

The inlet and outlet gas and liquid temperatures were measured by mercury thermometers graduated in 0.1°C. divisions. Gas and liquid flow rates were measured by rotameters. Heat loss from the column was prevented by a double-air jacket insulation.

The air vapor mixture leaving the column passed through a low pressure drop condenser to recover some of the carbon tetrachloride. The pressure drop through the apparatus was negligible.

EXPERIMENTAL PROCEDURE

The flows of air and carbon tetrachloride were adjusted to the required values and the sump tank thermostat adjusted to give the required liquid inlet temperature. The apparatus was run until gas and liquid temperatures become constant. The constant head burrette scale reading was taken every quarter hour until check results were obtained and a large enough volume of liquid had been evaporated to get volumetric accuracy. The atmospheric pressure was noted at the beginning and end of each run.

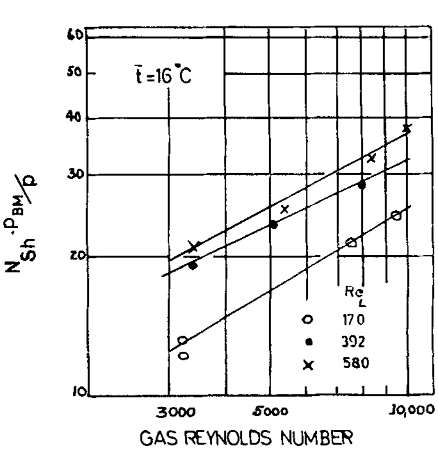

Fig. 2. Vaporization of carbon tetrachloride in a wetted-wall column showing the effect of gas and liquid rate. Average liquid temperature 16°C.

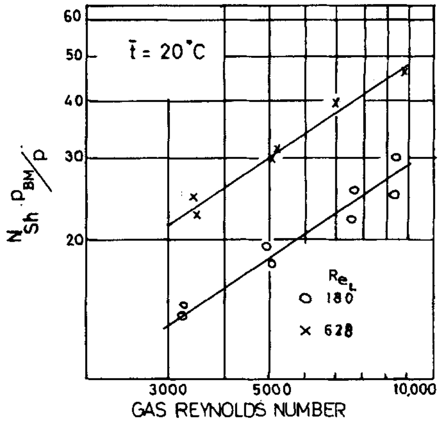

Fig. 3. Vaporization of carbon tetrachloride in a wetted-wall column showing the effect of gas and liquid rate. Average liquid temperature 20°C.

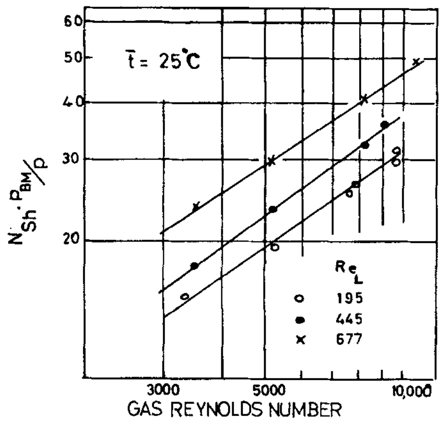

Fig. 4. Vaporization of carbon tetrachloride in a wetted-wall column showing the effect of gas and liquid rate. Average liquid temperature 25°C.

Experiments were done at five average liquid temperature levels between 16° and 35°C. over a range of gas and liquid rates.

CALCULATION METHODS

The results are presented and correlated in terms of the dimensionless groups N_{Re_g}, N_{Re_l}, N_{Sc}, $\frac{p_{BM}}{p}$, and N_{Sh}. The logarithmic mean of the driving forces at each end of the column was used in the calculation of the mass transfer coefficient. The carbon tetrachloride partial pressure driving force at each end of the column was taken as the difference between the vapor pressure of carbon tetrachloride at the liquid temperature at that point and the average partial pressure of carbon tetrachloride in the air stream. The partial pressure of carbon tetrachloride in the inlet air stream was always zero; that in the exit air stream was obtained by mass balance. The liquid temperature difference from top to bottom of the column varied between 3° and 8°C., at an average liquid temperature of 16°C. and between 8°C. and 21°C. at 35°C., the highest average liquid temperature used.

The arithmetic mean of the mass flow rate at the top and bottom of the column was used in calculating N_{Re_g} and N_{Re_l}. Viscosity, density, and diffusivity were taken at mean film conditions. The drift correction term p_{BM} was taken as the average of the p_{BM} value at the top and bottom of the

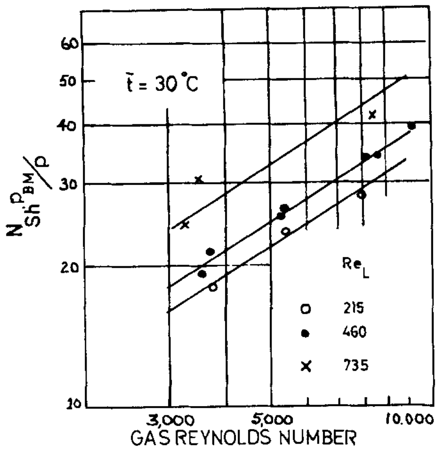

Fig. 5. Vaporization of carbon tetrachloride in a wetted-wall column showing the effect of gas and liquid rate. Average liquid temperature 30°C.

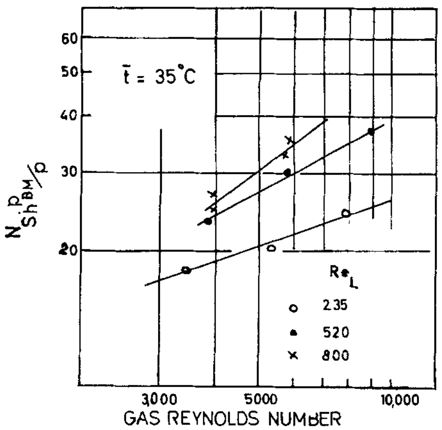

Fig. 6. Vaporization of carbon tetrachloride in a wetted-wall column showing the effect of gas and liquid rate. Average liquid temperature 35°C.

TABLE 1. SAMPLE SETS OF DATA

Run No.	16.6	20.6	25.6
Liquid inlet temperature, °C. t_{L1}	20.35	24.2	33.8
Liquid outlet temperature, °C. t_{L2}	12.80	17.00	16.22
Gas outlet temperature, °C. t_{G1}	20.32	23.6	27.4
Gas inlet temperature, °C. t_{G2}	28.52	22.8	21.6
Barometric pressure, mm. Hg P	760.75	760	736.65
Rate of vaporization, ml./hr. L	661	471	796
Average liquid temperature, °C. $t_{L_{AV}}$	16.57	26.0	25.01
Average gas temperature, °C. $t_{G_{AV}}$	24.38	23.2	24.52
Liquid flow rate, kg./hr. L	12.12	12.63	12.54
Gas flow rate, kg./hr. G	13.50	5.97	9.22
Liquid Reynolds number, N_{Re_L}	167	184	194
Gas Reynolds number, N_{Re_G}	10,920	4,960	7,770
Diffusivity, carbon tetrachloride in air, sq. m./sec., D	0.0732	0.0738	0.0749
Schmidt number, N_{Sc}	2.07	2.063	2.018
Transfer rate, $\frac{\text{k. moles}}{\text{sq. m./hr.}}$ k_g	0.1442	0.1026	0.173
Mass transfer coefficient, $\frac{\text{k. moles}}{(\text{hr.})/(\text{sq. m.})(\text{atm.})}$ k_g			
Sherwood number, N_{Sh}	39.9	21.1	27.7
Drift correction, p_{BM}/p	0.945	0.932	0.91

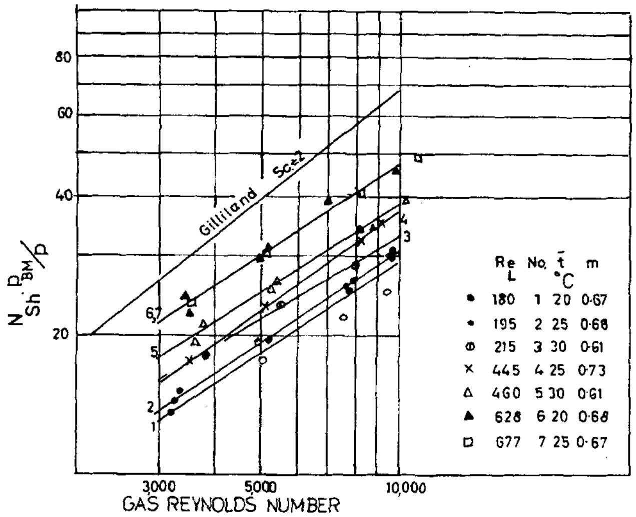

Fig. 7 Vaporization of carbon tetrachloride in a wetted-wall column at different average liquid temperatures showing the marked effect of liquid Reynolds number.

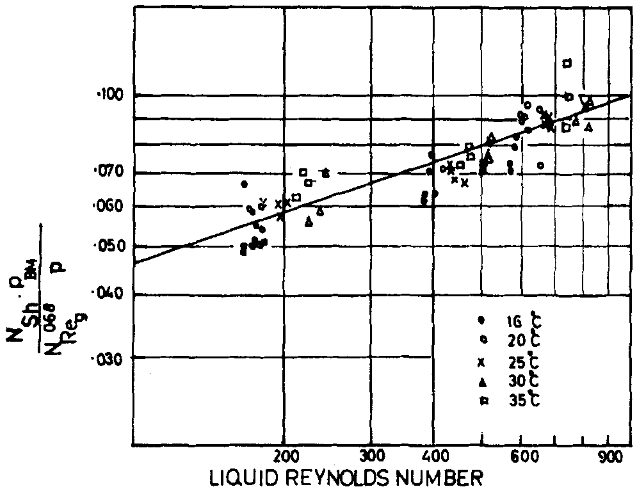

Fig. 8. Data on the rate of evaporation of carbon tetrachloride in a wetted-wall column showing a correlation with liquid Reynolds number. The effect of gas Reynolds number is assumed to be satisfied by a mean exponent on N_{Reg} of 0.68.

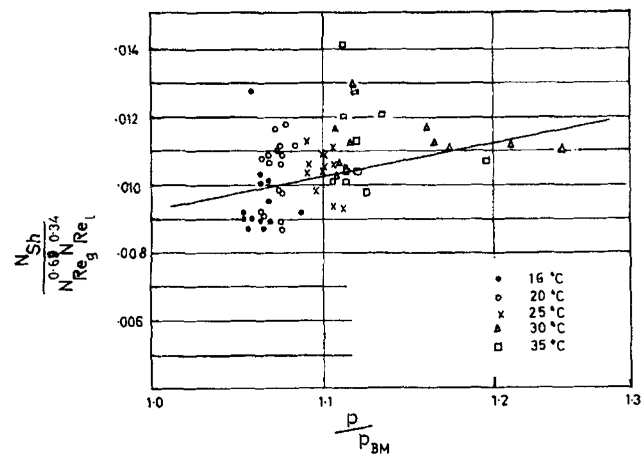

Fig. 9. A comparison on linear coordinates of all the experimental results with Equation (2), showing the effect of the drift correction factor.

column. Table 1* shows some of the data and calculated values.

DISCUSSION

The results presented in Figures 2 to 7 show a marked effect of liquid rate on the gas film mass transfer coefficient. This liquid rate effect, characterized by Re_l, is probably partly due to the relative velocity effect and partly due to rippling, and it is not possible to separate these two factors in these results. The exponent on N_{Re_g} in most of these plots is of the order of 0.68, which is lower than that found in much mass transfer work. In Figure 7 the results from this work are compared with a line representing results of Gilliland and Sherwood (*1*) for solvents with a Schmidt number of approximately 2. These results, obtained at higher liquid rates than those used in this work, lie above the carbon tetrachloride results.

In Figure 8, the correlating effect of Re_l is shown by a plot of $\frac{N_{Sh} \cdot p_{BM}}{N_{Re_g}^{0.68} P}$ against Re_l. The results at different temperatures scatter equally about the line, suggesting that a sensible heat transfer resistance is not the explanation for the effect of liquid rate on mass transfer. The correlating equation obtained from Figure 8 is

$$N_{Sh} \frac{p_{BM}}{p} = 0.0093\, N_{Re_g}^{0.68} N_{Re_l}^{0.34} \quad (2)$$

This equation is replotted and compared with the experimental results in Figure 9, which shows the small effect of the drift correction factor $\frac{p_{BM}}{p}$ for most of these experiments. Equation (2) predicts 88% of the experimental results to 15%.

Liquid rate appears to have a larger effect on gas film controlled mass transfer for evaporation into air of carbon tetrachloride than for the evaporation of water (*3*). In these experiments the carbon tetrachloride in air Schmidt number was more than twice that of water in air, and it may be that the effect on the mass transfer rate of the roughness of the liquid surface due to molecular diffusion to eddy diffusion is rippling is greater when the ratio of less. This explanation has been used recently to explain surface roughness effects on mass transfer rates to liquids from pipe walls (*6*).

* A more detailed version of Table 1 has been deposited as document 8548 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.

NOTATION

d = column diameter
D = molecular diffusivity
G = average gas mass flow rate
k_g = gas phase mass transfer coefficient
m = slope of a line in Figure 7, exponent on gas Reynolds number
p = total pressure
p_{BM} = log mean partial pressure of air in the column
N_{Re_g} = gas Reynolds number relative to pipe wall = $\frac{G \cdot d}{\mu_g}$
N_{Re_l} = liquid Reynolds number = $4\Gamma/\mu_l$
N_{Sc} = average gas phase Schmidt number = $\frac{\mu_g}{\rho_g D_g}$
N_{Sh} = gas Sherwood number = $k_g \frac{RTd}{D_g}$

Greek Letters

μ = viscosity
ρ = density
Γ = mass flow rate of liquid per unit perimeter

Subscripts

g = gas
l = liquid

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Fluid Mechanical Analogies

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The problem of steady, axial, irrotational flow of a Newtonian fluid through a nonporous duct is analogous to several other problems. The knowledge of these analogies was well known thirty to forty years ago; however, apparently, as a result of the separation of the fields of mechanics of fluids and mechanics of elastic solids, these analogies are not as widely known now. Recently, several analytical solutions to the above mentioned fluid mechanics problem have been published and are available from previously published solutions for an analogous problem. These analogies will be briefly reviewed and references to the fundamental work will be given. Examples of recently published solutions to the Newtonian fluid flow problem which are available from previously published solutions for an analogous problem will also be given.

Love (*1*) reviewed and summarized the known analogies. The subject of that discussion is the analogy of the torsion problem, which is the topic of the chapter, to various fluid mechanics problems. The analogy rests on the principle that the twisting force couple causing the torsion can be replaced by a statically equivalent axial compression force. Poisson's equation can be solved by a Green's function, which is specific to the boundary or boundaries of the prism, to yield a plane harmonic function ψ. The function is the conjugate of the torsion function ϕ.

$$\phi + i\psi = f(x + iy)$$

where x and y are position variables.

A solution of Poisson's equation may be obtained if the condition

$$\psi - 1/2\ (x^2 + y^2) = \text{constant}$$

is satisfied at the boundary. The function ψ has been determined for a variety of prism shapes (*1* to *3*).

The function ψ is mathematically identical with the velocity or stream function of three fluid mechanical problems. Two are for frictionless fluids and will not be discussed here. The third analogy is that the function $\psi - 1/2\ (x^2 + y^2)$ is . . . "Mathematically identical with the velocity in a certain laminar motion of a viscous fluid" (*1*) . . . when the motion is caused by a pressure gradient along a duct of the same shape as the twisted prism. The analogy was first observed by Boussinesq (*4*). Application of a known solution of the torsion problem to a fluid mechanics problem is discussed by Bairstow and Berry (*5*) and Dryden et al. (*6*).

The application of this analogy would have obviated the need for recently published solutions for Newtonian fluid flow through an eccentric annular duct (*7* to *9*) and an isosceles triangular duct (*10*). The eccentric annular duct solution previously had been given by Bairstow and Berry (*5*) (see also *6*, p. 198) who utilized the solution to the analogous torsion problem of MacDonald (*11*). The solution for the isosceles triangular duct could be deduced from the analogous torsion solution of Saint-Venant (*3*, pp. 121-122).

In conclusion, it is hoped that this note will lead to economy of effort on the problem of axial, steady, irrotational flow of a Newtonian fluid in ducts. Many solutions to the analogous problem of torsion in a prism of the same shape are available (*1* to *3*). In many cases direct application of these results should be possible.

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