Subscripts

c = continuous phase
d = dispersed phase

LITERATURE CITED

Baird, M. H., and A. E. Hamielec, "Forced Convection Transfer Around Spheres at Intermediate Reynolds Numbers," *Can. J. Chem. Eng.*, **40**, 119 (1962).
Boehm, R. F., H. R. Jacobs, and W. W. Coats, "Application of Direct Contact Heat Exchangers to Power Generation Systems Utilizing Geothermal Brines," *Proc. 9th Inter-Society Energy Conservation Engineering Conf.*, 1044 (1974).
Kehat, E., and S. Sideman, "Heat Transfer by Direct Liquid-Liquid Contact," *Recent Advances in Liquid-Liquid Extraction*, Chap. 13 p. 455, Pergamon Press, Oxford (1971).
Mori, Y. H., "Configuration of Gas-Liquid Two-Phase Bubbles in Immiscible Liquid Media," *Intern. J. Multiphase Flow*, **4**, 383–396 (1978).
Raina, G. K., and P. D. Grover, "Direct Contact Heat Transfer with Change of Phase: Theoretical Model," *AIChE J.*, **28**, no. 3, 515 (May 1982).
Sambi, S. S., "Direct Contact Heat Transfer to Vaporizing Drop in Immiscible Liquids," Ph.D. Thesis, IIT, Delhi, 1981.
Selecki, A., and L. Gradon, "Uber den Verdampfungs mechanismus eines sich in einer nicht mischberen Flussigkeit bewegenden Flussigkeitstropfens," *Chem. Ingr. Tech.*, **44** (18), 1077 (1972).
Sideman, S., and J. Isenberg, "Direct Contact Heat Transfer with Change of Phase: Bubble Growth in Three Phase Systems," *Desalination*, **2**, 207 (1967).
Sideman, S., and Y. Taitel, "Direct Contact Heat Transfer with Change of Phase: Evaporation of Drops in an Immiscible Liquid Medium," *Intern. J. Heat Mass Transfer*, **7**, 1273 (1964).
Simpson, H. C., G. C. Beggs, and M. Nazir, "Evaporation of Butane Drops in Brine," *Desalination*, **15**, 11–23 (1974).
Tochitani, Y., T. Nakagawa, Y. H. Mori, and K. Komotori, "Vaporization of Single Liquid Drops in an Immiscible Liquid, Part II: Heat Transfer Characteristics," *Wame-Und Stoffubertragung*, **10**, 71–79 (1977).

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Gas Absorption Across Free Surface of a Stirred Vessel

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Owing to its industrial importance, gas absorption into a turbulent liquid in stirred vessels has been widely studied (Kozinski and King, 1966; Sada et al., 1979; Davies and Lozano, 1979; Kataoka and Miyamchi, 1972). As a result, many physical models were proposed to predict the rate of mass transfer across the free gas-liquid interface (Danckwerts, 1951; Davies, 1972; King, 1966; Lamont and Scott, 1970; Levich, 1962). One common basis of these models is that the turbulent eddies of Prandtl size or larger determine mass transfer rates at a free surface. Davies and Lozano (1979), through their measurements of turbulence close to the air-water interface, provided some positive experimental evidence.

However, it was felt that a firmer confirmation would be desirable since the results of Davies and Lozano showed scatterings and, in particular, the slope of the experimental curve $k_c/\sqrt{D}$ vs. N, which helped in drawing the conclusion, was not in good agreement with those estimated from various theories. The purpose of our work is to attempt a simple experimental means by which the validity of the conclusion of Davies and Lozano can be further solidified.

The theoretical background of this work is simple. Based on these large-eddy models, one could argue that if the eddies found in an agitated tank, generally of size proportional to the agitator diameter, are to be progressively reduced in size, one would expect the rate of mass transfer across the interface to decrease correspondingly. This is because as the reduction occurs, there will be few large eddies with sufficient kinetic energy to overcome surface tension and cause surface renewals. Furthermore, if a series of size reduction is allowed, it is conceivable that the gas-liquid interface would eventually become so calm that it could be considered as a laminar layer of liquid. For mass transfer across a laminar film of liquid, k_c has been found to be very nearly independent of Reynolds number (Fortescue and Pearson, 1967; Davies and Warner, 1969). Thus, the objective of this experiment is to establish whether the trend mentioned above, that is, k_c should decrease with the scale of eddy and eventually becomes independent of Reynolds number, exists.

EXPERIMENT

A schematic diagram of the apparatus used is shown in Figure 1. The glass vessel was 30 cm in diameter and fitted with four solid baffles, 2.54 cm wide. Three screen cylinders of dia. 2.5, 5.0 and 7.5 cm were placed in the tank, concentric with the stirrer shaft. They were made from woven screens of 6 mesh for the second set of runs and of ten mesh for the third series of runs. The tops of these cylinders were slightly above the water surface.

The stirred tank was covered with a plexiglass plate with openings for gas inlet and outlet, impeller shaft, and sampling. The impeller, located 10 cm above the tank bottom, was a six-blade, bronze turbine, 10 cm in diameter, and was driven by a variable-speed motor. The blades were 2.5 cm in length and 1.9 cm in height.

After a series of pressure reduction, the gaseous CO_2 was fed to the tank through a long copper coil. The coil served as a temperature regulating device. Distilled water was the other fluid used; its temperature was not controlled but was reasonably constant at the room temperature of 20°C.

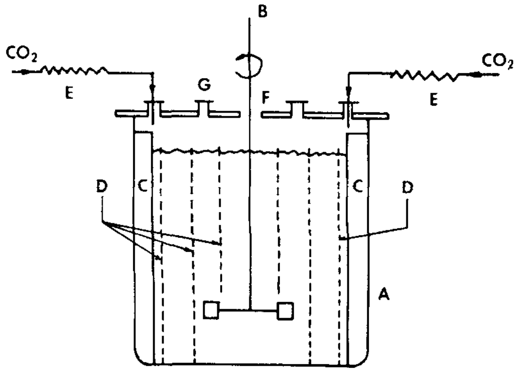

Figure 1. Flow diagram. A: stirred tank; B: turbine impeller; C: baffles; D: screen cylinders; E: copper coil; F: vent; G: sampling port.

The water in the tank was frequently replaced and was always maintained at a level approximately equal to the tank diameter.

After a steady operation was observed, the system was first purged with carbon dioxide gas, followed by taking liquid samples at approximately 10- to 20-min intervals with a 25-ml pipet. The samples were analyzed using a wet chemistry technique. The carbon dioxide was precipitated as barium carbonate from a solution of barium hydroxide, and the excess barium hydroxide solution was back-titrated with hydrochloric acid.

Values of the liquid-phase volumetric mass transfer coefficient $k_c a$ were estimated from the slopes of the experimental curves $\ln(c^* - c)$ vs. t according to the following equation:

$$\ln(c^* - c) = k_c a t + C_1 \tag{1}$$

where $a = A/V$, and C_1 is the constant of integration.

The first series of runs was conducted without screen cylinders, and the results were intended for confirming the experimental technique. The results obtained were reproducible to within ±5%.

RESULTS AND DISCUSSION

Typical curves showing the increase in the liquid-phase concentration as a function of time are shown in Figure 2. The linearity of the relationship appears to be quite satisfactory, and therefore Eq. 1 can be used to evaluate k_c.

Results from this study are given in Figure 3 for four different cases. Curve 1 represents the result obtained with no screens, it indicates a relationship of $k_c/\sqrt{D} \alpha N^{1.05}$. The exponent of 1.05 is lower than the theoretical value of 1.5, but close to the experimental values of 1.2 of Davies and Khan (1965) and 1.4 of Davies et al. (1964). As pointed out by Davies (1972), who has also obtained a value of 0.8, the exponent is sensitive to the location of the stirrer. Therefore, it can be concluded that the present experimental setup and the technique used are reasonably satisfactory for our purpose.

Curve 2 in Figure 3 shows a marked reduction of the exponent from 1.05 to 0.54 when the three concentric cylinders of six mesh are in place. The exponent further decreases to 0.32 (curve 3) as a result of replacing the six-mesh cylinders by ten-mesh cylinders. Therefore, the trend clearly shows a rapid decrease of the value of the exponent toward the theoretical limit of zero with increasing mesh number.

It should be noted that the use of wire-gauze screens for reducing turbulence has been a common practice in the aerodynamic industry. When a screen is placed perpendicular to the direction of the mean velocity of a turbulent stream, its dual role as a turbulence suppressor and a turbulence generator has been identified. In the present study, screens of fine mesh and thin wires have been used; the turbulence generated by such screens would be of small scale (about the size of the wire) and low intensity, thereby guaranteeing its very rapid downstream decay. No new turbulence due to screens is expected to reach the interface.

The gauze screen has also had the so-called filter effect on turbulence (Schubauer et al., 1950; Laws and Livesey, 1978). This

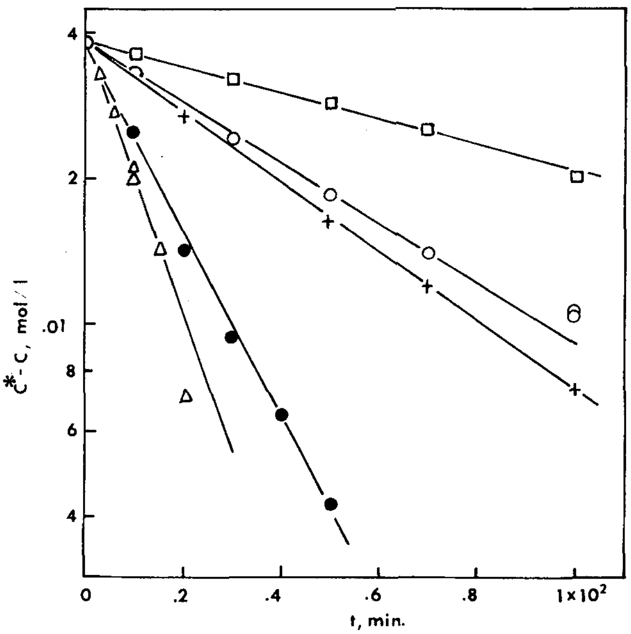

Figure 2. Typical gas absorption curves.

	N, rpm	Screen
-□-□-	120	6 mesh/in
-○-○-	720	10 mesh/in
-△-△-	720	no
-●-●-	300	wires
-+-+-	720	6 mesh/in

effect refers to the ability of screens of fine mesh to destroy eddies in the flowing stream of sizes larger than the mesh opening of the screen, thus changing the spectrum of the turbulence. According to Dryden and Schubauer (1947), the turbulence intensity may be reduced in the ratio of $1/(1 + K)^{1/2}$ by a single screen and in the ratio $1/(1 + K)^{n/2}$ by n identical screens in series. These relations

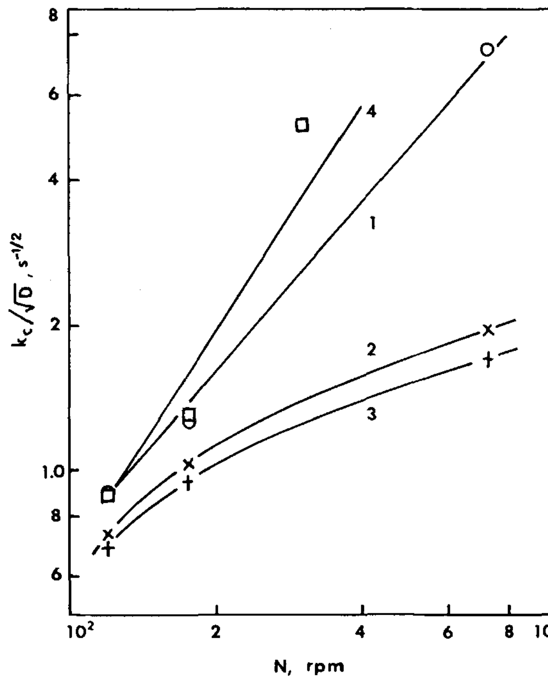

Figure 3. Frequencies of surface renewal.

-○-○-	no screen
-×-×-	6 mesh/in
-+-+-	10 mesh/in
-□-□-	wires

show that for the same pressure loss, a greater turbulence reduction can be achieved with a number of screens of small K than with a single screen of loss coefficient nK.

The pressure-loss coefficient K can be estimated approximately for the six-mesh and ten-mesh screens used in this study from the correlation of Laples (1963) to be 2.08 and 2.88, respectively. Assuming that the three screen cylinders are equally effective, a reduction of turbulence intensity by 81.5% for six-mesh screen and by 87% for ten-mesh screen is obtained from Dryden and Schubauer's formula. In terms of the kinetic energy reduction, it is 92.6% for the former and 96.3% for the latter.

Such remarkable energy reductions would unquestionably cause most of the eddies to remain within the bulk of the liquid, a result of the reductions in size and in kinetic energy, and hence their inability to overcome the combined force of surface tension and gravity. Therefore, the frequency of the surface renewal is expected to fall drastically and would cotinue to fall as long as finer-mesh screens are used. This trend is clearly illustrated in Figure 3.

The finding that the eddies produced in a stirred vessel containing screens are unable to reach the free gas-liquid interface is supported by the experimental results reported as curve 4 in Figure 3. In this set of experiments, the screen cylinders were suspended above the liquid surface, with only the bottom tips immersed. As the surface liquid was rotating and flowing past the sets of wires, some new turbulence was generated ($N_{Re} > 80$) at the surface. The small-scale turbulence thus generated was superimposed on the large-scale turbulence from the agitation, resulting in a large improvement of the rate of mass transfer, as indicated in Figure 3. The importance of small eddies, if they can reach the interface, is therefore very obvious in relation to the rate of mass transfer.

CONCLUSION

Simple experiments involving the use of screens as a turbulence suppressor were successful. Results obtained are interpreted as strong evidence supporting the conclusion of Davies and Lozano that it is the large eddies that determine rates of mass transfer at a free liquid surface.

ACKNOWLEDGMENT

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NOTATION

a = interfacial area per unit volume, m^2/m^3
C = concentration, mol/m^3
C^* = equilibrium concentration, mol/m^3
D = molecular diffusivity, m^2/s
k_c = mass transfer coefficient, m/s
K = pressure-loss coefficient
n = number of layers of screens in series
t = time, s

LITERATURE CITED

Danckwerts, P. V., "Significance of Liquid-Film Coefficients in Gas Absorption," *Ind. Eng. Chem.*, **43**, 1460 (1951).
Davies, J. T., *Turbulence Phenomena*, Academic Press, New York (1972).
Davies, J. T., and F. J. Lozano, "Turbulence Characteristics and Mass Transfer at Air-Water Surfaces, *AIChE J.*, **25**, 405 (1979).
Davies, J. T., and W. Khan, "Surface Clearing by Eddies," *Chem. Eng. Sci.*, **20**, 713 (1965).
Davies, J. T., A. A. Kilner, and G. A. Ratcliff, "The Effect of Diffusivity and Surface Films on Rates of Gas Absorption," *Chem. Eng. Sci.*, **19**, 583 (1964).
Davies, J. T., and K. V. Warner, "The Effect of Large-Scale Roughness in Promoting Gas Absorption," *Chem. Eng. Sci.*, **24**, 231 (1969).
Dryden, H. L., and G. B. Schubauer, "The Use of Damping Screens for the Reduction of Wind-Tunnel Turbulence," *J. Aeron. Sci.*, **14**, 221 (1947).
Fortescue, G. E., and J. R. A. Pearson, "On Gas Absorption into a Turbulent Liquid," *Chem. Eng. Sci.*, **22**, 1163 (1967).
Kataoka, H., and T. Miyauchi, "Effects of Physical Properties and of Turbulence on the Rate Coefficient of Mass Transfer at the Free Surface of Agitated Vessels in Turbulent Region," *Kagaku Kogaku*, **36**, 888 (1972).
King, C. J., "Turbulent Liquid Phase Mass Transfer at a Free Gas-Liquid Interface," *I&EC Fund.*, **5**, 1 (1966).
Kozinski, A. A., and C. J. King, "Influence of Diffusivity on Liquid Phase Mass Transfer to the Free Surface in a Stirred Vessel," *AIChE J.*, **12**, 109 (1966).
Lamont, J. C., and D. S. Scott, "An Eddy Cell Model of Mass Transfer into the Surface of a Turbulent Liquid," *AIChE J.*, **16**, 513 (1970).
Laples, C. E., in *Perry's Chem. Engrs. Handbook*, 4th Ed. 5 (1963).
Laws, E. M., and J. L. Livesey, "Flow Through Screens," *Ann. Rev. Fluid Mech.*, **10**, 247 (1978).
Levich, V. G., *Physicochemical Hydrodynamics*, Prentice-Hall, Englewood Cliffs, NJ (1962).
Sada, E., S. Kotoh, H. Yoshii, and Y. Ban, "Rates of Gas Absorption with Interfacial Turbulence Caused by Micro-Stirrer," *Can. J. Chem. Eng.*, **57**, 704 (1979).
Schubauer, G. B., W. G. Sprangenberg, and P. S. Klebanoff, "Aerodynamic Characteristics of Damping Screens," *NACA Rept. No. 2001* (1950).

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