LOW-COST EXPERIMENTS IN MASS TRANSFER

Part 1*

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Laboratory work is an important component in the chemical engineering curricula. In a recent *CEE* article, Stubington[1] appropriately defined the objectives of a teaching laboratory as

> **. . . to develop skills in the acquisition and analysis of engineering data; to develop the ability to communicate experimental findings in written and oral forms; and to reinforce in a practical way theoretical concepts taught in lectures.**

Laboratory instructors are all too familiar with the impasse created by lack of funds for equipment, combined with increased student enrollment. The challenge is to devise significant experiments using existing laboratory supplies such as pipes, fittings, or glassware. A simple and inexpensive method for determining liquid-side mass transfer coefficients in an undergraduate chemical engineering laboratory is described here.

THEORY

Gas absorption can be a complex process with resistances in either phase, with the additional problem of estimating the interfacial area in flow across packing, etc. In this experiment, a model system with a simple geometry has been chosen so that the mass transfer coefficient can be measured and compared with a theoretical prediction. Students should be cautioned that the equations given here are not sufficient to design a piece of practical equipment. They do, however, provide a partial theoretical basis for design.

Pure carbon dioxide is absorbed from a chamber into a jet of water. Because the gas is pure, the entire mass transfer resistance lies in the liquid phase. The rate of mass transfer (R) from the gas to the liquid phase is related to the driving force (ΔC), the area for mass transfer (A), and the mass

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transfer coefficient (k_ℓ) by the equation

$$R = k_\ell A \Delta C \tag{1}$$

Generally speaking, each of the three terms on the right can vary independently and, in a given case, the estimation of (R) has to be done by using a combination of theoretical models and empirical correlations. This experiment allows the driving force (ΔC) and the area (A) to be known exactly, thus permitting one to find the mass transfer coefficient (k_ℓ) by measuring the rate of mass transfer (R). The value of k_ℓ so determined can then be compared with the results predicted by the popular Higbie's Penetration Theory for unsteady diffusion.[2]

This theory indicates that the value of k_ℓ depends on the molecular diffusion coefficient (D) and the contact time (τ) as described below:

$$k_\ell = 2\sqrt{\frac{D}{\pi\tau}} \tag{2}$$

Here, τ is the time for which the liquid surface is in contact with gas and can be set by forming a jet of liquid passing continuously through the gas at a uniform velocity u. Since τ can be calculated by dividing the jet length (L) with the average velocity of the liquid (u), the above equation can be written as

$$k_\ell = 2\sqrt{\frac{Du}{\pi L}} \tag{3}$$

*Part 2 of this paper will appear in the spring 1996 issue of CEE.
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The above equation can also be written in dimensionless form, using a *length-based* Sherwood number ($Sh = k_\ell L / D$) and Reynolds number ($Re = uL\rho / \mu$):

$$Sh_\ell = \frac{2}{\sqrt{\pi}} Re_\ell^{1/2} Sc^{1/2} \tag{4}$$

The liquid properties (ρ, μ) cancel out on the right-hand side of Eq. (4). That is consistent with the assumption of an ideal jet moving at a plug flow velocity, u. In practice, there is a very small hydrodynamic boundary layer near the nozzle. The shear stress at the gas-liquid interface is very small because of the low viscosity of the gas phase. Therefore, the simplifying assumption of liquid plug flow can be justified as a reasonable approximation.

Combining Eqs. (1) and (3), we get

$$R = 2\sqrt{\frac{Du}{\pi L}} A \Delta C \tag{5}$$

It may be noted that the contact time between a short jet of water and the surrounding gas (CO_2) is so small that only an insignificant quantity of CO_2 is picked up by the water jet and the bulk concentration of CO_2 in water at any time (C_w) remains negligible. Thus, the driving force ($\Delta C = C_w^* - C_w$) is essentially given by C_w^*, the solubility of CO_2 in water at the operating temperature, which can be found in the literature.[3]

The surface area (πdL) of the water jet exposed to the gas is a function of d and L, the diameter and length of the jet, respectively. It is assumed that the liquid velocity (u) is great enough that d remains constant over the jet length. Substituting these into Eq. (5) and simplifying gives

$$R = 2\, C_w^* d \sqrt{D \pi u L} \tag{6}$$

The velocity term in Eq. (6) can be replaced by the average volumetric flow rate ($Q = u\pi d^2 / 4$), giving

$$R = 4\, C_w^* \sqrt{DQL} \tag{7}$$

Cullen and Davidson[4] showed that this form of mass transfer expression holds even for cases where gravitational acceleration has a significant effect on jet velocity u.

APPARATUS

A schematic of the apparatus is shown in Figure 1. The gas chamber may be a glass tube 5-to-6 cm diameter and 25-to-30 cm long. Water is fed from an overhead reservoir to a jet nozzle located in the chamber. The water jet is in contact with the gas for a short length (L) that can be adjusted by raising or lowering the nozzle. The jet leaves the chamber at the draw-off tube, which is filled with kerosene to provide a non-absorbing liquid seal. A small layer of kerosene is also present at the base of the chamber to cover any water drops that may accidently spill from the draw-off tube. On the gas side, a supply of pure CO_2 can be connected to the chamber, and a soap film gas meter is also connected so that small changes in volume of the gas in the chamber can be measured.

PROCEDURE

1. Set up the apparatus with the addition of kerosene layers as shown in Figure 1. The purpose of various kerosene layers is to allow CO_2 absorption only in the water in the jet and not in any other location, such as in the draw-off tube or in spillage.
2. Purge the gas chamber thoroughly with CO_2.
3. With the gas flow on, squeeze the soap solution bulb and run a few films up the graduated gas burette to lubricate it.
4. Test the apparatus for leaks.
5. Start the water flow to obtain a uniform jet falling directly into the 1-cm draw-off tube. (Note that at very small flow rates, the jet would tend to bead, and this should be avoided.)
6. Bring the kerosene level to the tip of the draw-off tube by lowering or raising the outlet tube.
7. Measure, and maintain, the jet length as the distance between the nozzle tip and the draw-off tube.
8. Reduce the CO_2 flow to a very small value and run a few soap films up the graduated burette. (At large gas-flow rates the soap films will either break or exit the burette too quickly.)
9. When a few films reach the top of the burette, shut off the gas supply completely. (The soap films will start descending at a rate depending on the rate of adsorption of CO_2.)
10. Measure the rate of CO_2 absorption by monitoring the rate of descent of the soap films.
11. Measure the water flow rate (Q) from the outlet tube with the help of graduated cylinder and stop watch. (Because the

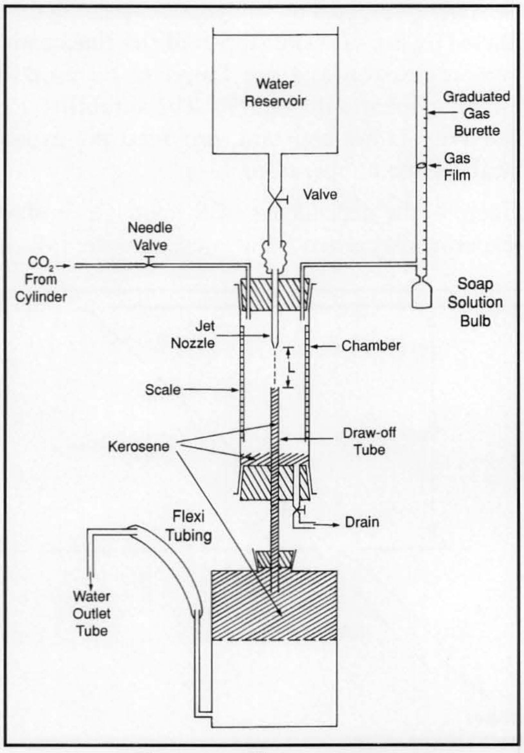

Figure 1. *The apparatus*

total measuring time for the film-descent and water flow rate measurements is not more than a few minutes, the water level in the overhead reservoir, and therefore the hydrostatic head and hence (Q), can be assumed to remain unchanged during the measurement period.)

12. Repeat steps 8 through 11 at four or five more water flow rates for the same jet length.
13. Measure the diameter (d) of the nozzle (and hence the jet) either with a traveling microscope or by the following experiment that makes use of the law of conservation of energy:

A water jet is made to rise at an angle θ (see Figure 2). For a given volume flow rate, the average kinetic energy of a fluid element of mass, m, in the jet as it leaves the nozzle with an average velocity u is $\frac{1}{2}mu^2$. As it rises against gravity, it decelerates and eventually its velocity becomes zero at a certain height, h, after which it starts accelerating downward. At the instant its velocity is zero, its kinetic energy based on the vertical velocity component, $u \sin\theta$, is changed entirely to its potential energy and the two may be equated as

$$\frac{1}{2} mu^2 \sin^2\theta = mgh \tag{8}$$

which on replacing u in terms of the volumetric flow rate $Q\left(= u\pi d^2/4\right)$ and simplifying gives

$$d^2 = \frac{Q \sin\theta}{\pi}\sqrt{\frac{8}{gh}} \tag{9}$$

from which d can be obtained.

TYPICAL RESULTS AND DISCUSSION

Figure 3 shows typical measured mass transfer rates R, plotted against $\sqrt{Q}$ for several different jet lengths. It can be seen that the data are well represented by straight lines passing through the origin, as predicted by Eq. (7). The slopes of the lines can be determined by linear regression and are found to be proportional to $\sqrt{L}$, again in agreement with Eq. (7). The solubility C_w^* and molecular diffusivity D are constant, provided the experiments are all done at the same temperature.

In Figure 4, the dependence of R upon $\sqrt{L}$ is shown directly for some experiments carried out at constant water flow rate with different jet lengths. Again, regression analysis should be carried out to determine the slope.

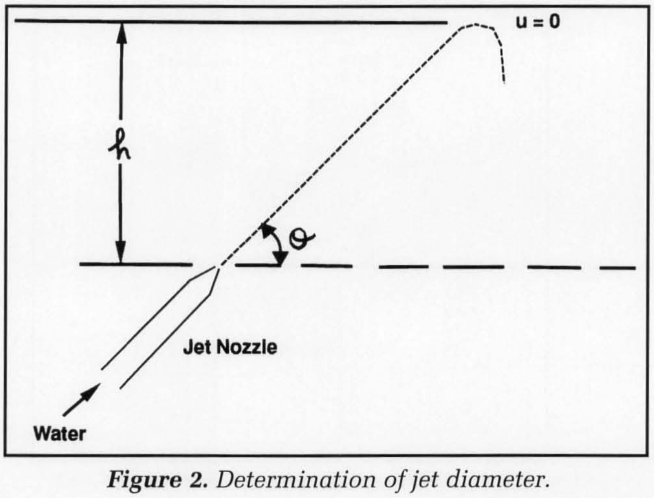

Figure 2. Determination of jet diameter.

A complete comparison of data with the theory can be made if values of C_w^* and D from the literature sources are given, and this is illustrated in Table 1.

Students should be asked to discuss possible rea-

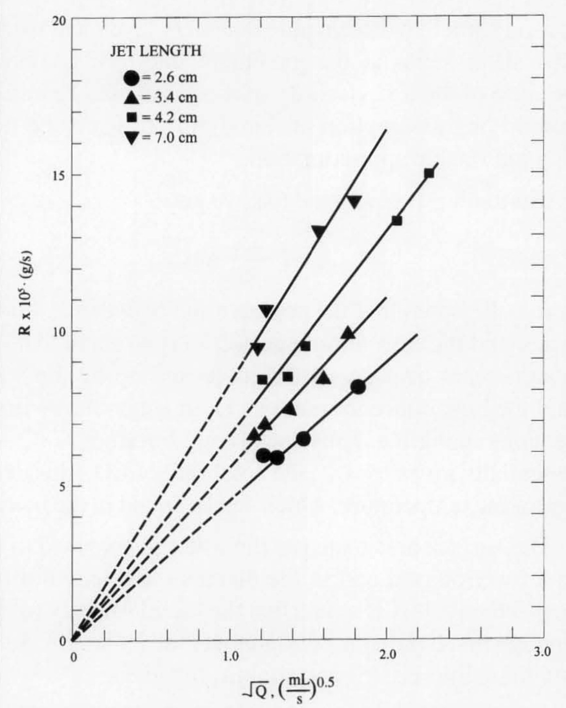

Figure 3. Dependence of gas absorption rate on water flow rate (Q) through a jet of 0.0984 cm diameter at several different lengths.

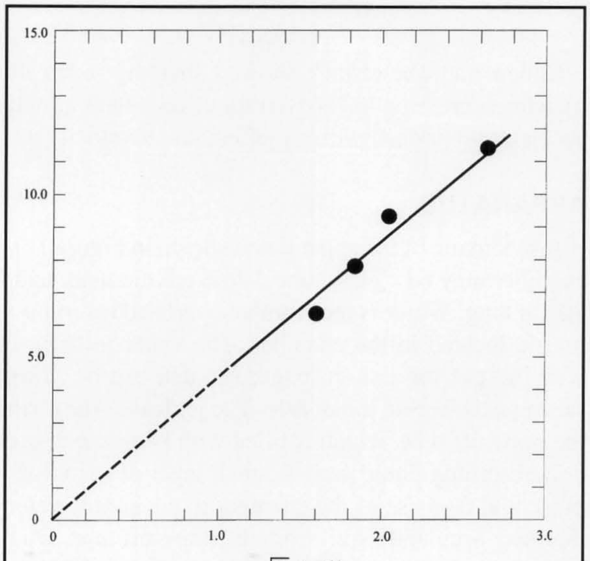

Figure 4. Dependence of gas absorption rate on length of a jet 0.0984 cm diameter, for water flow rate Q = 1.96 mL/s.

sons why the measured k_ℓ values are slightly different from the calculated values. For example, the penetration theory assumes that the liquid is moving in plug flow, but the jet leaving the nozzle may have a curved velocity profile, or it may be turbulent.

CONCLUSIONS

The apparatus is easy to build and needs hardware that is usually available in any chemical engineering department. The experiment introduces the students to an experimental test of Higbie's Penetration Theory, liquid-phase mass-transfer resistance, and conservation of energy. The entire class can be subdivided into various groups and each group can be asked to study the effect of liquid flow rate on CO_2 absorption for one fixed jet length (or jet diameter), the other groups studying different jet lengths (or jet diameters). This will make it an all-group lab because each group will need data from other groups to compile a comprehensive lab report. Specifically, each group can be asked to do the following:

1. Plot R vs. $\sqrt{Q}$ and determine if Eq. (7) holds. Such a plot should be linear for a given jet length. Data for all jet lengths should be plotted on the same graph for comparison (see Figure 3 for typical experimental data).
2. Obtain data for R vs. L for a given flow rate from (1) above, and plot R vs. $\sqrt{L}$ (see Figure 4 for typical experimental data).
3. Calculate $k_{\ell\,\text{expt}}$ from Eq. (1) and compare $k_{\ell\,\text{pred}}$ obtained from Eq. (3) (see Table 1).

In addition, the students can be asked to comment on the effect of jet acceleration due to gravity resulting in tapering the jet and thus decreasing its diameter (and hence the surface area that has been taken as πdL). The instructor may encourage the students to review a paper by Cullen and Davidson[4] for a discussion of the basic assumptions and to ascertain that the effect of the taper is exactly offset by the effect of acceleration, so that Eq. (7) is rigorously valid.

Unpredictable results may sometimes be observed due to one or a combination of the following reasons:

1. *Gas burette is not clean and gas films do not descend at a uniform rate.*
2. *Soap films are too frothy and soap-solution consistency needs adjustment.*
3. *Jet length is too small (less than 2.5 cm).*
4. *Water flow rate is too small, e.g., it corresponds to incipient drop formation.*
5. *The apparatus leaks.*

TABLE 1
Typical Experimental Results

Jet Diameter = 0.1914 cm	$C_w^* = 1.649 \times 10^{-3}$ g/cm^3	$\rho = 0.99823$ g/cm^3
Temperature = 20°C	$D = 1.77 \times 10^{-5}$ cm^2/s	$\mu = 0.01005$ g/ms

L (cm)	Q (cm^3/s)	u (cm/s)	τ (s)	$R_{expt.} \times 10^5$ (g/s)	$k_{\ell\,\text{expt}}$ Eq.1(cm/s)	$k_{\ell\,\text{pred}}$ Eq.3(cm/s)
2.6	1.463	50.852	0.051	6.005	0.02328	0.02098
2.6	1.631	56.691	0.046	6.005	0.02328	0.02098
2.6	2.12	73.688	0.0353	6.629	0.02569	0.02387
2.6	3.244	112.76	0.023	8.227	0.03189	0.0295
4.2	1.434	49.84	0.084	8.502	0.02039	0.01517
4.2	1.875	65.17	0.065	8.575	0.02056	0.01762
4.2	2.172	75.49	0.056	9.567	0.02294	0.0268
4.2	4.348	150.85	0.028	13.5	0.03237	0.02845
4.2	5.125	178.14	0.024	15.06	0.03612	0.02358

NOMENCLATURE

- A area
- C_w carbon dioxide concentration in water at any time
- C_w^* carbon dioxide solubility in water at operating temperature
- d jet diameter
- D diffusion coefficient of CO_2 in water at operating temperature
- g acceleration due to gravity
- k_ℓ water-side mass transfer coefficient
- L jet length
- m water mass flow rate
- R gas absorption rate
- Re_ℓ Reynolds number, $uL\rho/\mu$
- Q water volume flow rate through the jet
- Sc Schmidt number, $\mu/\rho D$
- Sh_ℓ Sherwood number, $k_\ell L/D$
- u water velocity through the jet

Greek Symbols

- θ angle
- τ contact time
- Δ change
- μ liquid viscosity
- ρ liquid density

ACKNOWLEDGMENTS

Financial support for this work was provided by the Natural Sciences and Engineering Research Council of Canada. Thanks are due to Mr. T. Bainbridge and Mr. S. Connell for collecting some of the experimental data.

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