A SIMPLE FORCED CONVECTION EXPERIMENT

O. C. SANDALL and D. A. MELLICHAMP
University of California,
Santa Barbara, Calif. 93106

MASS TRANSFER EXPERIMENTS in chemical engineering programs are customarily reserved for a "unit operations" or "transport processes" laboratory course taken in the junior or senior year. An attempt at introducing laboratory experience in mass transfer at an early stage has been made at the University of California at Santa Barbara. Students, working in groups of two to four, are assigned an experiment as a term project in the mass transfer course which is ordinarily taken during the third quarter of the junior year. Design of the experiment, fabrication of necessary equipment, the collection of data, and reporting of results to the rest of the class furnish the student some "real-world" experiences beyond those obtained from the usual laboratory demonstration or experiment.

Unfortunately, mass transfer experiments often are more difficult to carry out than analogous ones in the areas of heat and momentum transport. Coupled with this difficulty is the necessity to assign the students a reasonable project to carry through in six to eight weeks; the burden of avoiding this potential conflict obviously is the responsibility of the instructor. The experiment described in this paper meets these requirements very well; in particular, it furnishes a convincing verification of the analogy between mass and heat transfer and is well within the capabilities of undergraduate students. The experimental methods and results presented below reflect an evolution of techniques through three groups of students in as many years.

PURPOSE

The basic objective of this experiment is to measure local mass transfer coefficients for forced convection mass transfer for flow past a circular cylinder. Mass transfer coefficients are determined by measuring the local rate of decrease in radius of a naphthalene cylinder which is sublimed in a low speed wind tunnel. Naththalene is particularly well-suited for this experiment since it can be cast into cylinders fairly easily, and it is a solid having a significant vapor pressure at room temperature.

By measuring the distribution of the mass transfer coefficient around the cylinder, the results obtained illustrate the separation of the laminar boundary layer. The data also provide an experimental verification of the analogy between heat and mass transfer since heat transfer results are readily available in the literature for comparison with the mass transfer data obtained.

PREPARATION OF NAPHTHALENE CYLINDERS

Several methods of casting the naphthalene cylinders were tried. It was found that uniformly smooth surfaces were achieved by fast cooling, and the procedure used was to pour the liquid naphthalene into a mold which had been placed in liquid nitrogen. The mold was constructed from a 12-inch long section of 2-inch diameter aluminum pipe sealed at one end with a rubber stopper.

After the cylinders were cast and before removing them from the aluminum pipe, a ½-inch hole was drilled axially through the center. The reason for drilling out the center is that the radius measurements were referred to a ½-inch aluminum rod that was placed through the center of the naphthalene cylinders. As an aid in obtaining the desired angular orientation of the cylinders in the wind tunnel, a 1/16-inch hole was drilled through the cylinders on a diameter. A 1/16-inch rod was placed through this hole and, when the cylinder was mounted in the wind tunnel, the cylinder was oriented so that this rod was perpendicular to the floor of the wind tunnel test section.

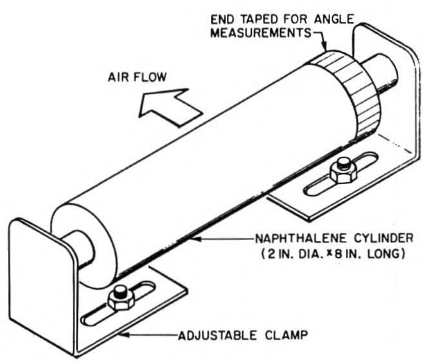
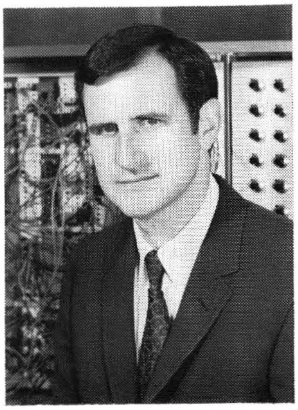


FIG. 1.—Mounting Arrangement for Naphthalene Cylinders.

The aluminum tubing was removed from the naphthalene cylinders by taking cuts on a milling machine along opposite sides of the tube until the wall thickness was thin enough to remove the two halves by hand.

In order to measure the angular position along the circumference of the cylinders, a length of masking tape of size equal to the circumference was cut and marked



Orville C. Sandall is currently an assistant professor in Chemical Engineering at the University of California at Santa Barbara. He obtained his education at the University of Alberta (BSc, MSc) and the University of California at Berkeley (PhD). His teaching and research interests are in the areas of heat and mass transfer. (left).

Duncan A. Mellichamp is an assistant professor in Chemical Engineering at the University of California at Santa Barbara. He received the BChE at Georgia Tech, studied one year at the Technische Hochschule Stuttgart (Germany), and obtained the PhD at Purdue University. His present interests are in the fields of process dynamics and automatic control. (right).

off into 18 equal divisions to give 20-degree intervals, The placement of the tape at one end of the cylinder was facilitated by the orientation hole which had been drilled on the diameter.

EXPERIMENTAL MEASUREMENTS

Measurements of the cylinder radius before sublimation were made by placing a ½-inch aluminum rod through the hole drilled through the center of the naphthalene cylinder. The aluminum rod was supported by two V-blocks, and radius measurements were made to± 0.001 inch with a vernier height gage. The actual distance measured was the radial distance between the center bar and the naphthalene cylinder. It was found that the radius measurements did not vary significantly in an axial direction, but did vary along the circumference, and for this reason initial radius measurements were made at 20-degree intervals around the circumference.

The students made initial estimates of how long the experiment should proceed in order that a sufficiently measurable change in the radius would occur. This calculation indicated that a time on the order of 10 hours was required for the Reynolds numbers of interest.

The naphthalene cylinder was mounted in a stand as shown in Figure 1 and placed in the wind tunnel test section. The air velocity was measured and adjusted to give the desired Reynolds number by using either a pitot tube or a hot wire anemometer. Air temperature measurements were taken during the course of the experiment. After the experiment had proceeded for the pre-determined length of time, the air flow was stopped and the final radius measurements were taken at angular positions measured from the forward stagnation point.

This experiment furnishes a convincing verification of the analogy between mass and heat transfer and is well within the capabilities of undergraduate students

INTERPRETATION OF RESULTS

A mass balance at a position on the surface of the cylinder relates the rate of decrease in radius to the sublimation flux:

$$-\rho \frac{dr}{d\theta} = N_{a,s} \qquad (1)$$

Using the nomenclature of Bennett and Myers,[1] the mass transfer coefficient is defined in terms of the diffusion flux as:

$$N_{a,s} = k'_\rho (\rho_{a,s} - \rho_{a,\infty}) + x_{a,s} N_{a,s} \qquad (2)$$

Substitution of Equation 2 into Equation 1 and approximation of the derivative with finite differences gives upon rearrangement:

$$k'_\rho = -\rho \frac{(1 - x_{a,s})}{(\rho_{a,s} - \rho_{a,\infty})} \frac{\Delta r}{\Delta \theta} \qquad (3)$$

In Equation 3 the density of naphthalene in the free stream is zero ($\rho_{a,\infty} = 0$), $x_{a,s}$ is very small compared to 1.0 ($x_{a,s} << 1.0$) and $\rho_{a,s}$ may be calculated from the ideal gas law ($\rho_{a,s} = \frac{P_a^* M_a}{RT}$).

With these substitutions Equation 3 becomes:

$$k'_\rho = \frac{\rho RT}{p_a^* M_a} \left(- \frac{\Delta r}{\Delta \theta} \right) \qquad (4)$$

Thus measuring the change in radius of the cylinder allows calculation of the mass transfer coefficient. The vapor pressure, p_a^*, in Equation 4 was obtained as a function of temperature from the International Critical Tables.[2]

Figure 2 shows the data obtained at a Reynolds number of 110,000 plotted as the local Sherwood number. The data show the high mass transfer coefficient that occurs at the forward stagnation point. The mass transfer coefficient then decreases

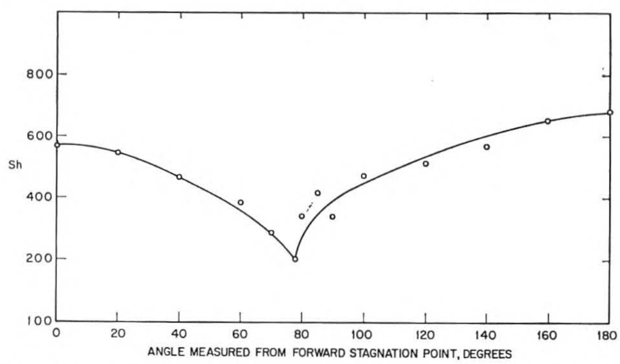


FIG. 2.—Local Mass Transfer Coefficients for a Circular Cylinder Measured at Re = 110,000.

to a minimum as the laminar boundary layer thickens. This minimum occurs at a position approximately 80° from the forward stagnation point and indicates the separation point of the laminar boundary layer. Beyond the separation point the surface is exposed to the turbulent wake which results in an increasing mass transfer coefficient to a maximum at the rear stagnation point.

Figure 3 shows a comparison between the mass transfer data obtained and the heat transfer data of Zapp[5] for the same Reynolds number. The good agreement obtained between the heat and mass transfer data provides a convincing experimental verification of the analogy between heat transfer and low mass flux mass transfer. For this comparison the heat transfer Nusselt numbers are divided by $Pr^{1/3}$ and the mass transfer Sherwood numbers are divided by $Sc^{1/3}$. The basis for these factors is the Colburn analogy between heat and mass transfer. The physical properties used in this plot were obtained from Perry[4].

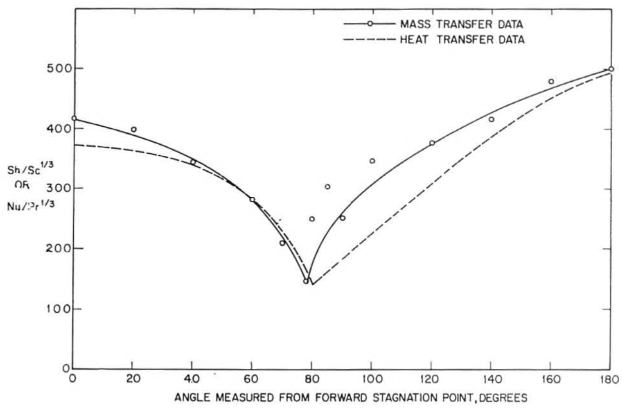


FIG. 3.—Local Mass Transfer Coefficients Compared with Heat Transfer Data at Re = 110,000.

The heat transfer data of Zapp shown in Figure 3 were obtained for a main-stream turbulence intensity of 0.9%, which is considered to be low, whereas, the turbulence level for the mass transfer experiment was not measured but was thought to be low. The deviation between the two curves may be attributed to a higher turbulence level in the mass transfer experiment or possibly to an error in temperature measurement since an error of 1°C corresponds to approximately a 10% change in vapor pressure.

A further test of the mass transfer data was made by comparing the mean mass transfer Sherwood numbers obtained with correlations developed for heat transfer. The relationship recommended by McAdams[3] for predicting the average heat transfer coefficient for air flowing past circular cylinders is

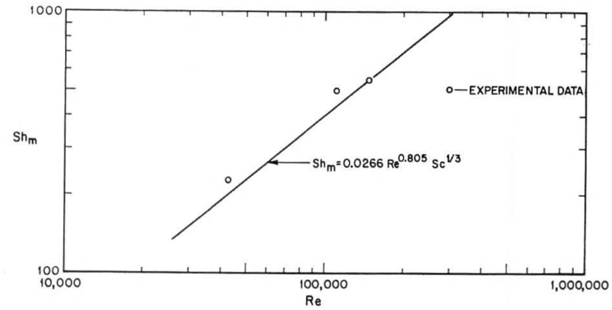


FIG. 4.—Mean Sherwood Numbers Compared with Heat Transfer Correlation.

$$Nu_m = cRe^n \qquad (5)$$

For Reynolds numbers in range of the mass transfer experiments the constants c and n are given as c = 0.239, and n = 0.805. If the constant c is modified according to the Colburn analogy to take the difference in Schmidt and Prandtl numbers into account, then the mass transfer equation equivalent to Equation 5 is

$$Sh_m = 0.0266\ Sc^{1/3}Re^{0.805} \qquad (6)$$

Figure 4 gives a comparison of the data and Equation 6. As can be seen, a favorable comparison was obtained.

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NOMENCLATURE

c—constant in Equation 5, dimensionless
C_p—heat capacity, BTU/lb °F
d—diameter of cylinder, ft.
D_{ab}—diffusion coefficient, ft.^{2}/hr.
h—heat transfer coefficient, BTU/hr.-ft.^{2} °F
k—thermal conductivity, BTU/hr-ft-°F
k'—mass transfer coefficient, ft/hr
M_a—molecular weight of naphthalene, lb/lb mole
n—constant in Equation 5, dimensionless
$N_{a,s}$—mass flux at the surface, lb/hr-ft.^{2}
p_a^*—vapor pressure of naphthalene, lb_f/ft.^{2}
r—radius of cylinder, ft.
R—gas constant, lb_f-ft./lb mole °R
T—temperature, °R
u_∞—free stream velocity, ft./hr.
$x_{a,s}$—mass fraction at surface, dimensionless
ρ—density of solid naphthalene, lb./ft.^{3}
$\rho_{a,s}$—density of naphthalene in gas phase at surface, lb/ft^3

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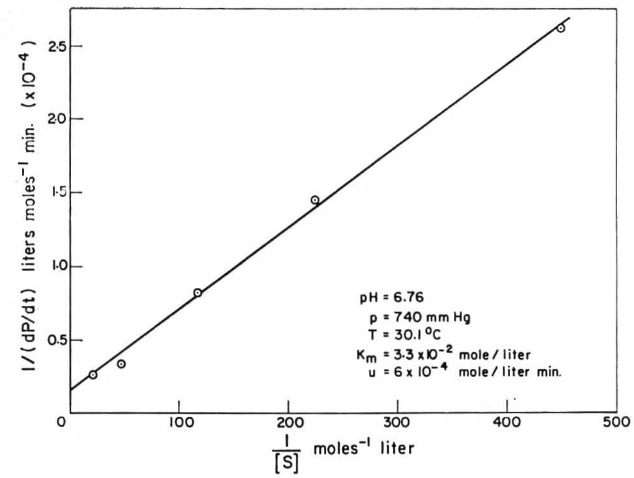

FIG. 2.—Lineweaver-Burk Plot.

time and about one hour to perform the calculations.

We have found that although this experiment introduced new concepts to the students, the theory was not beyond their grasp. We were able to present the students with an elementary understanding of biochemical phenomena and arouse interest in a growing area in chemical engineering.

REFERENCES

1. McElroy, W. D. and Glass, B., Ed., Mechanism of Enzyme Action, p. 402, Greenwood Press, New York, 1968.
2. Dixon, M. and Webb, E. C., Enzymes, p. 311, 2nd Ed., Academic Press, New York, 1964.
3. Cleland, W., "The Statistical Analysis of Enzyme Kinetic Data," Advances in Enzymology, Vol. **29**, p. 1, 1967.
4. Barman, T. E., "Enzyme Handbook," Vol. **1**, p. 232, Springer Verlag, New York, 1969.

ZONE REFINING: HUDGINS

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With a non-uniform impurity profile in the ingot, the solution of equation (2) is no longer analytically tractable. This need not deter further experimentation; indeed, some students may find it worthwhile to compute the results for two or more passes of the molten zone, and test these with experiment.

SUMMARY

This experiment serves to introduce an unusual but important separation process and provide practice in thinking through a mathematical description of it closely related to that used for flow tank reactors.

LITERATURE CITED

1. Pfann, W. G., Zone Melting, John Wiley & Sons, New York, 2nd ed. 1966.
2. Schildknecht, H., Zone Melting, Translated by Express Translation Service, London, Academic Press, New York, 1966.
3. Schoen, H. M., from New Chemical Engineering Separation Technique, Interscience Publishing Co., New York, 1st ed. 1962, pp. 103-155.
4. Christian, J. D., **J. Chem. Ed. 33**, 32 (1956).
5. Hinton, J. F., McIntyre, J. M., Amis, E. S., **J. Chem. Ed. 45**, 116 (1968).
6. Knypl, E. T., and Zielenski, K., **J. Chem. Ed. 40**, 392 (1963).
7. Zeif, M., Ruch, H., and Schramm, C. H., **J. Chem. Ed. 40**, 351 (1963).
8. Denbigh, K. G., Chemical Reactor Theory, Cambridge University Press, London, 1965.
9. Herington, E. F. G., Zone Melting of Organic Compounds, Blackwell Scientific Publications, Oxford, 1st ed. 1963.

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CONVECTION: Sandall and Mellichamp

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$\rho_{a,\infty}$—density of naphthalene in gas phase in free stream, lb/ft.^{3}
μ—absolute viscosity, lb/hr-ft.
ν—kinetic viscosity, ft^2/hr.
θ—time, hr.
Nu—Nusselt number, hd/k
Pr—Prandtl number, $\mu C_p/k$
Re—Reynolds number, $u_\infty d/\nu$
Sc—Schmidt number, ν/D_{ab}
Sh—Sherwood number, $\frac{k'_p d}{D_{ab}}$

REFERENCES

1. Bennett, C. O., and Myers, J. E., "Momentum, Heat, and Mass Transfer," McGraw-Hill Book Co., Inc., New York, 1962.
2. "International Critical Tables," Vol. 3 p. 208, McGraw-Hill Book Co., Inc., New York, 1928.
3. McAdams, W. H., "Heat Transmission," 3rd ed., p. 260, McGraw-Hill Book Co., Inc., New York, 1954.
4. Perry, J. H., ed., "Chemical Engineers' Handbook," 4th ed., McGraw-Hill Book Co., Inc., New York, 1963.
5. Zapp, G. M., M. S. Thesis, Oregon State College, 1950; Knudson, J. G. and Katz, D. L., "Fluid Dynamics and Heat Transfer," McGraw-Hill Book Co., Inc., New York, 1958, pp. 496-501.