Forced Convection Mass Transfer: Part IV.

Increased Mass Transfer in an Aqueous Medium Caused by Detached Cylindrical Turbulence Promoters in a Rectangular Channel

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Enhanced rates of mass transfer in aqueous systems were studied with an electrochemical technique. Detached turbulence promoters (cylinders supported away from the surface) were shown to cause increases in mass transfer in aqueous systems in a manner similar to that observed in gaseous system. As in air studies, peaks in the local rate of mass transfer were observed directly beneath the cylinders and a wake effect was observed downstream from the cylinders.

We have shown that detached turbulence promoters (cylinders supported away from the surface) promote increased mass transfer in aqueous systems in a manner similar to that observed in gaseous systems (*1, 2*). In the previous studies, local values of the mass transfer rate were increased as much as 240%, and the average rate over an extended portion of the plate (183 promoter diameters downstream) was enhanced as much as 170%. The observed increases in mass transfer rates were complicated functions of promoter diameter, spacing from the plate, and spacing apart. Generally it appeared advantageous to pair the promoters rather than to space them evenly. Apparently vortex streets from one cylinder affect those from cylinders downstream, and a tuning effect is observed which causes larger mass transfer rates in the wake region. Consequently optimization is possible for particular combinations of cylinder spacing and velocity. These studies were performed with a sharp-edged plate in an air channel in which the depth was large compared with the thickness of the laminar boundary layer. Mass transfer rates were determined by measuring the rate of naphthalene sublimation from the surface.

Although the techniques described above were convenient for studying the basic behavior of detached cylindrical turbulence promoters, it was desirable to evaluate the promoter's potential performance in water desalination processes such as reverse osmosis or electrodialysis. Liquid systems generally have a Schmidt number greater than 500 compared with 2.4 for the air-naphthalene system. The significance of large Schmidt numbers is that the fictive concentration boundary layer is relatively much thinner than when the Schmidt number is near 1. There is also the question of what effect a second wall or other channel boundaries will have on the disturbances generated by detached promoters.

To evaluate the potential of detached turbulence promoters in aqueous systems, a series of mass transfer measurements was made in a rectangular channel. The experimental technique used was an electrochemical reaction (the ferro-ferricyanide redox system) under conditions where the rate of reaction was diffusion (that is mass transfer) controlled (*3* to *7*). Ferricyanide ions were reduced on a polarized test surface from a solution 0.01 M in potassium ferricyanide and potassium ferrocyanide. The solution was also 1 M in sodium hydroxide, which acted as a supporting electrolyte and reduced transference effects. The rectangular channel was a 2.5-in. by 0.49-in. cross section and had a 2-in. by 2.5-in. active nickel electrode test surface preceded by a sharp-edged plastic entrance section 4 in. long. The first cylindrical turbulence promoter was always located 2¾ in. downstream from the front edge of the electrode to permit internal calibration during some runs. Appropriate corrections were made to all average mass transfer promotion data to account for the reduced length of electrode (9¼ in.) over which mass transfer promotion occurred.

The test surface was maintained at the desired potential (relative to the polarizing electrode) with a d.c. power supply, and the average or total mass transfer rate over the plate was determined by measuring the current drawn from the power supply. To obtain local mass transfer rates at various locations on the surface, 0.010-in. diam. wires were embedded in the electrode and then ground flush with the surface. The wires were electrically insulated from the test surface, but were maintained at the same potential as the test surface with operational amplifiers from an analog computer. In addition, the analog com-

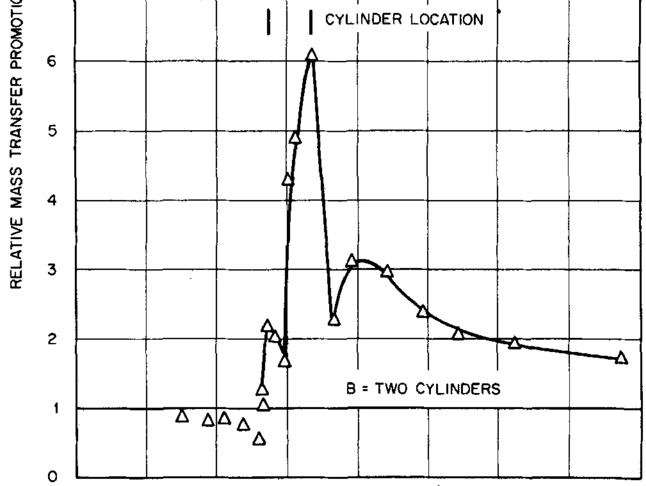

Fig. 1. Relative promotion caused by 3/32-in. diam. cylinders located one cylinder diameter from the surface at a channel Reynolds number of 1,630 (Schmidt number = 1,850).

puter circuit produced a voltage proportional to the current drawn by the wires, thus permitting evaluation of the local mass transfer rates.

Initial results from the aqueous studies demonstrate that comparable, and perhaps even greater, mass transfer promotion can be obtained with detached promoters than was obtained in gaseous studies. As in the studies with air as the fluid, pronounced peaks in the local rate of mass transfer were observed directly beneath the wires and greatly enhanced rates were observed in the wake region downstream from the wires. Typical results are shown in Figure 1. Peak values for relative promotion beneath the wires were 2.5 and 6 for single and the second of two cylinders, that is, about a factor of two larger than the values reported (*1, 2*) for laminar boundary layers in gaseous systems.

Figure 2 shows relative promotion, k/k_o (average mass transfer rate over effective length of electrode with promoters divided by the average mass transfer rate over the effective length of electrode without promoters), plotted as a function of Reynolds number based upon the channel thickness for three different combinations of cylindrical promoters. The promoters were 1/16-in. diam. cylinders with a gap of 1/32 in. between the bottom of the cylinder and the electrode. The three sets of data shown in Figure 2 were obtained with a single cylinder located 2¾ in. from the beginning of the active electrode surface, with two cylinders located 2¾ and 7¼ in. from the beginning of the active electrode surface and with three cylinders located 2¾, 5¾, and 8¾ in. from the beginning of the active electrode surface. With three promoters the mass transfer rate is more than doubled over the Reynolds number range of 1,000 to 3,500 with the maximum promotion of 135% (a factor of 2.35) observed at a Reynolds number of 1,800 to 1,900. No significant promotion was observed for Reynolds numbers less than 600. The Reynolds number for the beginning of promotion corresponds to a promoter Reynolds number (based on the promoter diameter and the velocity at the promoter centerline assuming a parabolic velocity profile) of about 50, which is the critical Reynolds number for shedding vortex streets from cylinders (*8*).

A series of tests to determine the optimum spacing between two wires in a pair for maximum mass transfer promotion was made with wire diameters of 1/16, 3/32, and ⅛. The gap between the wire and the plate was varied from 1/32 to ⅛ in. For all the combinations studied, the optimum center-to-center spacing of the wires was between eight to ten wire diameters. Since this is the same optimum spacing determined for pairs of cylinders in the air-naphthalene system, it appears that the scaling law for optimum distance between cylinders in a pair does not involve the physical properties of the system, that is, $8 < (x/D)_{opt} < 10$ (where x is the distance

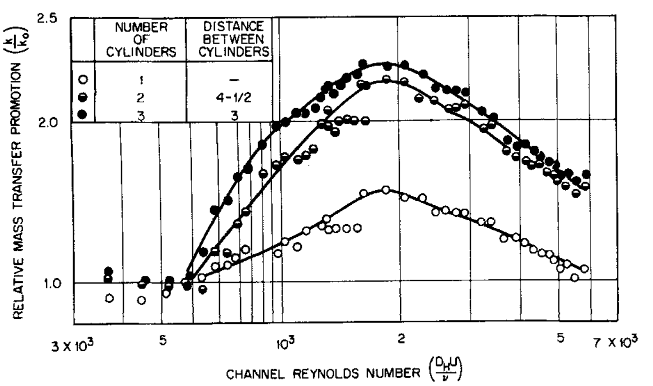

Fig. 2. Mass transfer promotion with evenly spaced 1/16-in. diam. cylinders spaced 1/16 in. from the wall.

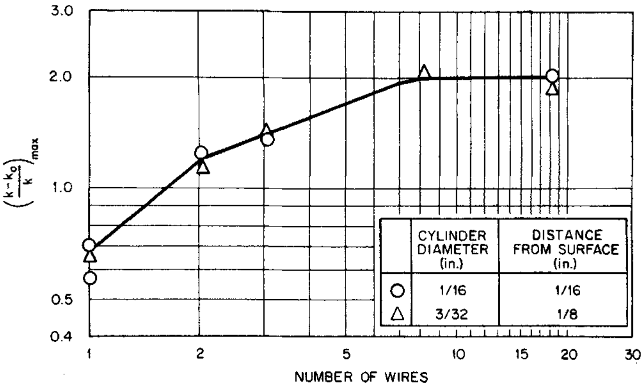

Fig. 3. Effect of the number and diameter of evenly spaced cylinders on the maximum increase in mass transfer promotion in channel flow for a Schmidt number of 1,850.

between cylinder centers and D is the cylinder diameter), with the most probable value for $(x/D)_{opt}$ between 8.5 to 9. It is of interest to note that this spacing between cylinders is substantially the same as the one for which the pronounced beat phenomena were observed in flow visualization studies (*9*).

The effect of the number and diameter of cylinders on the maximum increase in average mass transfer promotion over a 9¼ in. length of electrode in channel flow (at N_{Re} of 1,800 to 1,900) is shown in Figure 3. This figure shows the fractional increase in mass transfer rate due to the cylinders, $(k - k_o)/k_o$, plotted against the number of cylinders; the cylinders were positioned to divide the electrode surface into equal intervals. Figure 3 shows that there was a substantial increase in relative promotion in going from one to two cylinders with relatively smaller increases as the number of cylinders was increased from two to eight. There was little increase in the relative promotion as the number of cylinders was increased from eight to sixteen.

Although additional data are required to determine the optimum spacing of cylinders and range of flow conditions for maximum increase in mass transfer promotion, it is clear from the present data that there are marked similarities in the results with aqueous and gaseous systems.

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LITERATURE CITED

1. Thomas, David G., *AIChE J.*, **11**, 848-852 (1965).
2. *Ibid.*, **12**, 124-130 (1966).
3. Lin, C. S., E. B. Denton, H. S. Gaskill, and G. L. Putnam, *Ind. Eng. Chem.*, **43**, 2136-2143 (1951).
4. Eisenberg, Morris, C. W. Tobias, and C. R. Wilke, *Chem. Eng. Progr. Symp. Ser. No. 16*, **51**, 1-16 (1955).
5. Reiss, L. Philip, and Thomas J. Hanratty, *AIChE J.*, **8**, 245-247 (1962).
6. *Ibid.*, **9**, 154-160 (1963).
7. Van Shaw, P., L. Philip Reiss, and Thomas J. Hanratty, *ibid.*, **9**, 362-364 (1963).
8. Roshko, Anatol, *Natl. Advisory Comm. Aeronaut. Rept. 1191* (1954).
9. Thomas, D. G., and K. A. Kraus, *J. Appl. Phys.*, **35**, 3458-3459 (1964).

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