Dipprey, D. R., and R. H. Sabersky, "Heat and Momentum Transfer in Smooth and Rough Tubes at Various Prandtl Numbers," *Intern. J. Heat Mass Transfer*, **6**, 329 (1963).
Friend, W. L., and A. B. Metzner, "Turbulent Heat Transfer inside Tubes and the Analogy among Heat, Mass, and Momentum Transfer," *AIChE J.*, **4**, 393 (1958).
Gowen, R. A. and J. W. Smith, "Turbulent Heat Transfer from Smooth and Rough Surfaces," *Intern. J. Heat Mass Transfer*, **11**, 1657 (1968).
Harriott, P, and R. M. Hamilton, "Solid-Liguid Mass Transfer in Turbulent Pipe Flow," *Chem. Eng. Sci.*, **20**, 1073 (1965).
Hubbard, D. W., and E. N. Lightfoot, "Correlation of Heat and Mass Transfer Data for High Schmidt and Reynolds Numbers," *Ind. Eng. Chem. Fundamentals*, **5**, 370 (1966).
Hughmark, G. A., "Heat and Mass Transfer for Turbulent Pipe Flow," *AIChE J.*, **17**, 902 (1971).
———, "Notes on Transfer in Turbulent Pipe Flow," *ibid*, **18**, 1072 (1972).
———, "Additional Notes on Transfer in Turbulent Pipe Flow," *ibid.*, **19**, 1054 (1973).
———, "An Analysis of Turbulent Pipe Flow with Viscosity Variation in the Wall Region," *ibid.*, **21**, 187 (1975).
Kolar, V., "Heat Transfer in Turbulent Flow of Fluids through Smooth and Rough Pipes," *Intern. J. Heat Mass Transfer*, **8**, 639 (1965).
Mizushina, T., F. Ogino, Y. Oka, and H. Fukuda, "Turbulent Heat and Mass Transfer between Wall and Fluid Streams of Large Prandtl and Schmidt Numbers," *ibid.*, **14**, 1705 (1971).
Popovich, A. T., and R. L. Hummel, "Experimental Study of the Viscous Sublayer in Turbulent Pipe Flow," *AIChE J.*, **13**, 854 (1967).
Sleicher, C. A., A. S. Awad, and R. H. Notter, "Temperature and Eddy Diffusivity Profiles in NaK," *Intern. J. Heat Mass Transfer*, **16**, 1565 (1963).

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Transfer Coefficient in Pulsating Pipe Flow: Comments on an Article by Patel et al.

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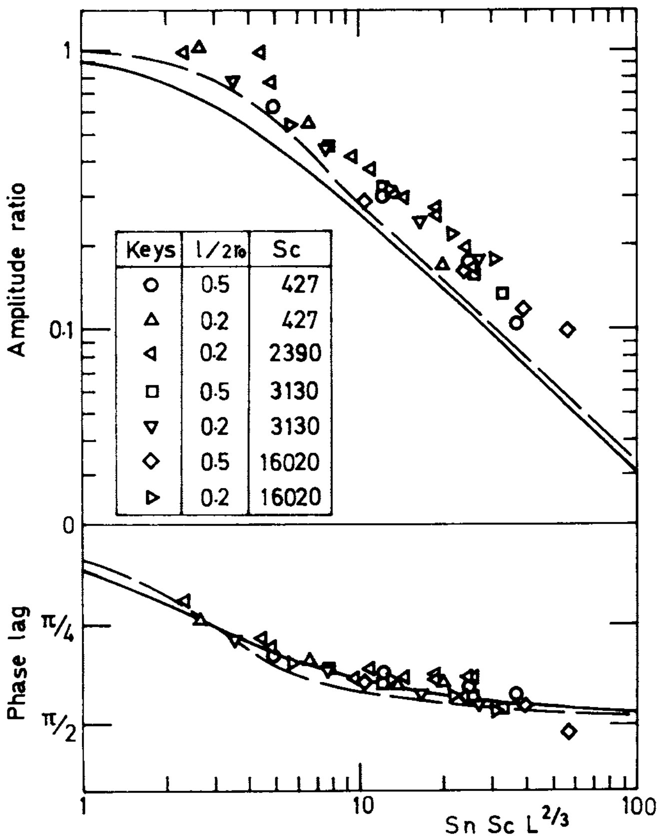

Fig. 1. Bode diagram of space averaged Sherwood number. ——, Equation (14); - -, Equation (5) in the paper by Mizushina et al. (1973).

In their paper on measurements of wall mass transfer in fully developed pulsating laminar flow in a tube, Patel et al. (1975) state that at higher frequencies the amplitude and phase of the wall mass transfer rate are correlated not by the theoretically derived variable $SnScL^{2/3}$, but by an empirical correlation variable $SnScL^{1/3} \times (l/2r_0)^{1/3}$. At the same time, they suggest some possible sources of error in both their experimental and theoretical treatments, but they leave the questions to be unsolved, stating that "the present work reports the first experimental measurements of amplitude and phase of the fluctuating mass transfer coefficient in pulsatile flow."

However, this is not the case. The experimental frequency response of the space averaged, mass transfer coefficient was already reported by us (Mizushina et al., 1973). We made measurements over wide ranges of Re, Sc, and Sn, using the electrochemical method. Figure 1 shows the frequency response of the space averaged value to the wall shear stress. As can be seen, the measurements are well correlated by the theoretically derived variable $SnScL^{2/3}$ and in good agreement with our theoretical curves. In addition, the validity of the correlation by the theoretically derived variable is confirmed for the local transfer coefficient under the heating condition of constant wall heat flux.

On the basis of this fact, we will make some comments on the empirical correlation variable proposed by Patel et al. (1975) and on their experimental procedure. The variable $SnScL^{2/3}$ shows dependences on Sc and Re as $Sc^{1/3}$ and $Re^{-2/3}$, while the empirical correlation variable $SnScL^{1/3}$ $(l/2r_0)^{1/3}$ has different dependences, that is, $Sc^{2/3}$ and $Re^{-1/3}$. However, the necessity of the 2/3 exponent of Sc instead of the 1/3 exponent is not clear, because the experimental range of Sc by Patel et al. is very narrow ($Sc = 3\,100 \sim 4\,050$) in view of the scatter of their data. Thus, only the different dependence on Re is admitted from their experiments. This, we infer, is not due to some sources of error suggested by them but rather to their misuse of an input signal as follows.

To make the flow pulsation, Patel et al. change a liquid level in the head tank using an oscillating displacement device immersed in the liquid. They measured the oscillation of the displacement device and tacitly regarded its amplitude and phase as being identical to those of a pressure gradient at test section. In unsteady state, however, the steady state relation between the displacement length of device and the pressure gradient does not hold because of dynamic behaviors of fluid in the flow system from the head tank to the test section. In particular, the dynamics of fluid in the head tank and through contraction, elbow and two valves largely affect the relation in unsteady state. Hence, the discrepancy in measurements by Patel et al. increased with increasing frequency of pulsation, and it depended on the flow rate, thus on Re.

Evidently the dynamic relation between the oscillation of the displacement device and that of the pressure gradient is peculiar to their flow system and is suspected to be too complex to clarify analytically for the use of their study. Accordingly, it is recommended that one avoids this complexity and measures directly the pressure difference or the wall shear stress at the test section as described in the paper of the commentators (Mizushina et al., 1973).

NOTATION

l = length of mass transfer section
L = dimensionless length = $l/(2r_0ReSc)$
Re = Reynolds number
r_0 = radius of circular tube
Sc = Schmidt number
Sn = Stokes number = $r_0^2\omega/\nu$
ν = kinematic viscosity
ω = angular frequency

LITERATURE CITED

Mizushina, Tokuro, Toshiro Maruyama, S. Ide, and Y. Mizukami, "Dynamic Behaviour of Transfer Coefficient in Pulsating Laminar Tube Flow," *J. Chem. Eng. Japan*, 6, 152 (1973).

Patel, R. D., J. J. McFeeley, and K. R. Jolls, "Wall Mass Transfer in Laminar Pulsatile Flow in a Tube," *AIChE J.*, 21, 259 (1975).

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Reply to the Note of Maruyama and Mizushina

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Maruyama and Mizushina are quite correct that the work of Mizushina et al. (1973) predates our study of mass transfer in pulsatile laminar flow (Patel et al., 1975). Their data do show excellent correlation with the variable $SnScL^{2/3}$, which is the variable X_1 in the notation of our paper.

There is no question that direct measurement of the fluctuating pressure difference in the tube is preferable in order to calculate the amplitude ratio and phase lag of the fluctuating transfer coefficient. However, in our work we did not take the amplitude and phase of the displacement device to be identical to those of the pressure gradient in the test section as stated by Maruyama and Mizushina. A dynamic analysis of the flow from the variable head tank through the valves and flow straighteners was done. This analysis yielded a relation between the amplitude and phase of the displacement device and those of the pressure gradient in the tube. Details are given in the thesis by McFeeley (1972). While this procedure is not as accurate as direct measurements of the pressure gradient, the error is not as large as the assumption of identical amplitudes and phases for the pressure gradient and the height of the displacement device. It is conceivable that the predicted pressure gradients of our analysis deviate from the true pressure gradients as a function of Reynolds number and frequency and that this may be the cause of the deviation of our data from the theoretical predictions.

LITERATURE CITED

McFeeley, J. J., "The Response of a Diffusion-Controlled Electrode to Pulsed Laminar Flow," Ph.D. dissertation, Polytechnic Institute of Brooklyn, Brooklyn, New York (1972).

Mizushina, Tokuro, Toshiro Maruyama, S. Ide, and Y. Mizukami, "Dynamic Behavior of Transfer Coefficient in Pulsating Laminar Tube Flow," *J. Chem. Eng. Japan*, **6**, 152 (1973).

Patel, R. D., J. J. McFeeley, and K. R. Jolls, "Wall Mass Transfer in Laminar Pulsatile Flow in a Tube," *AIChE J.*, **21**, 259 (1975).