Heat Transfer with Viscoelastic Fluids in Turbulent Flow

G. A. HUGHMARK

Ethyl Corp.
Baton Rouge, LA 70821

Ng, Cho and Hartnett (1980) showed that surprisingly long test sections are required to obtain fully developed heat transfer data for viscoelastic fluids. Kwack, Cho, and Hartnett (1981) reported heat transfer data for seven concentrations of Separan AP-273 in water with a test section length to pipe diameter ratio of greater than 430. This is sufficient to provide fully developed flow heat transfer data. Hughmark (1979) considered data for turbulent flow heat transfer with viscoelastic fluids as an extension of a three region model for Newtonian fluids. This note revises the prior work using the recent fully developed turbulent flow data and a recent suggestion by Campbell and Hanratty (1983) for wall region mass transfer.

NEWTONIAN FLUID MODEL

The three region resistance model for turbulent flow of Newtonian fluids is:

$$\frac{1}{k^+} = \frac{1}{k^+_B} + \frac{1}{k^+_T} + \frac{1}{k^+_C}$$

Campbell and Hanratty (1983) suggest that turbulent mass transfer at high Schmidt numbers is controlled by low frequency velocity fluctuations that contain only a small fraction of the total energy. Nonlinear calculations resulted in the equation:

$$k^+ = 0.09\left(\frac{W_\beta(0)}{0.01}\right)^{0.21} N_{Sc}^{-0.7} \tag{1}$$

utilizing the limiting value of the spectral density function of β for small frequency, $W_\beta(0)$. This suggests a two region resistance model:

$$\frac{1}{k^+} = \frac{1}{k^+_W} + \frac{1}{k^+_C} \tag{2}$$

in which equation 1 represents k^+_W. Hughmark (1971, 1972) shows:

$$k^+_C = 2\sqrt{f/2} + \frac{7.16}{N_{Re}N_{Sc}\sqrt{f/2}} \tag{3}$$

for the core contribution so Eqs. 2 and 3 can be combined to estimate k^+_W for heat transfer data. The data of Kolar (1965) for air and the data for water of Dipprey and Sabersky (1963) and Moyls and Sabersky (1978) cover the Prandtl number range from 0.7 to 10.3. Correlation of k^+_W for these data with the Prandtl number shows:

$$k^+_W = 0.0855 N_{Pr}^{-0.7005}$$

with a standard deviation of 0.0058 for the Prandtl number exponent. Thus these data show a Prandtl number exponent consistent with equation 1. Combination of these heat transfer data with the mass transfer data of Shaw (1977) for the Schmidt number range of 693 to 37,200 shows by correlation:

$$k^+_W = 0.0866(N_{Pr} \text{ or } N_{Sc})^{-0.704} \tag{4}$$

So Eq. 1 appears to apply for Newtonian fluids over a wide range of Prandtl and Schmidt numbers.

VISCOELASTIC FLUID MODEL

Kwack, Cho and Hartnett (1981) report that concentrations of Separan AP-273 less than 30 wppm were found to be shear rate independent. Reduction in drag and heat transfer with fluids of 5, 10 and 20 wppm then represent a viscoelastic response without a power-law fluid response. Heat transfer data with 30 wppm and higher concentrations are not shear rate independent so include a power-law non-Newtonian response in addition to the viscoelastic fluid response. Equations 2, 3 and 4 can then be used to calculate k^+_W for the 5, 10 and 20 wppm data. Hughmark (1975) suggested that the wall region frequency is related to the ratio of f_E/f_N. Addition of this ratio to Eq. 4 results in the equation:

$$k^+_W = 0.0866\frac{f_E}{f_N}(N_{Pr} \text{ or } N_{Sc})^{-0.704} \tag{5}$$

which shows an average absolute deviation of 7.6% with the 15 data sets from the 5, 10 and 20 wppm data.

NOTATION

f	= friction factor
k^+	= dimensionless transfer coefficient
N_{Pr}	= Prandtl number
N_{Re}	= Reynolds number
N_{Sc}	= Schmidt number
$W_\beta(0)$	= spectrum of fluctuations of β for small frequency
β	= time varying part of dimensionless normal velocity

Subscripts

B	= wall boundary region
C	= core
E	= viscoelastic
N	= Newtonian
T	= transition region
W	= wall region

LITERATURE CITED

Campbell, J. A., and T. J. Hanratty, "Mechanism of Turbulent Mass Transfer at a Solid boundary," *AIChE J.*, **29**, 221 (1983).
Dipprey, D. F., and R. H. Sabersky, "Heat and Momentum Transfer in Smooth and Rough Tubes at Various Prandtl Numbers," *Int. J. Heat Mass Transfer*, **6**, 329 (1963).
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).
——— "Wall Region Heat and Mass Transfer with Newtonian and Viscoelastic Fluids in Turbulent Flow," *ibid*, **25**, 555 (1979).
Kolar, V., "Heat Transfer in Turbulent Flow of Fluids through Smooth and Rough Pipes," *Int. J. Heat Mass Transfer*, **8**, 639 (1965).
Kwack, E. Y., Y. I. Cho, and J. P. Hartnett "Heat Transfer to Polyacrylamide Solutions in Turbulent Pipe Flow; The Once-Through Mode," *Chem. Eng. Prog. Symp. Ser.*, No. 208, **77**, 123 (1981).
Moyls, A. L., and R. H. Sabersky, "Heat Transfer and Friction Coefficients for Dilute Suspensions of Asbestos Fibers," *Int. J. Heat Mass Transfer*, **21**, 7 (1978).
Ng, K. S., Y. I. Cho, and J. P. Hartnett, "Heat Transfer Performance of Concentrated Polyethylene Oxide and Polyacrylamide Solutions," *Chem. Eng. Prog. Symp. Ser.*, No. 199, **76**, 250 (1980).
Shaw, D. A., and T. J. Hanratty, "Turbulent Mass Transfer Rates to a Wall for Large Schmidt Numbers," *AIChE J.*, **23**, 28 (1977).

Manuscript received May 11, 1983; revision received July 7, and accepted July 14, 1983.