u_m = maximum fluid velocity
z = axial distance coordinate

Greek Letters

α = D/kr_o^2, a diffusion parameter
β_n = eigenvalues of Equations (6) and (7)
λ = $z/\alpha N_{Sc} N_{Re} r_o = kz/u_m$, axial distance variable
μ = viscosity of fluid
ξ = r/r_o, dimensionless radial distance
ρ = density of fluid

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Effects of Solvent Purity on Non-Newtonian Viscosity

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Although variations in the rheology of non-Newtonian solutions have often been attributed to solvent characteristics, there have been no data available to show the magnitude of the changes produced. As a portion of a larger study program on the tube flow of non-Newtonian fluids, such data were obtained for a limited number of fluids common to the existing literature (*1* to *5*) and is presented herein.

By virtue of its simplicity, the power law (6 to 9), $\tau = a\left(\frac{du}{dy}\right)^n$, where τ is the shear stress and du/dy is the shear rate, is used to present the experimental data. In this paper the power law constants (coefficient and exponent) are determined from a straight line data fit over two orders of magnitude in the shear rate when the shear stress and shear rate are plotted logarithmically as in Figure 1. Despite the fact that the power law does not account for either the normal stresses or elasticity effects (*10* to *13*) thought necessary to describe these fluids, it can be assumed that any change in the power law constants is indicative of a change in the other rheological properties not independently measurable at this time.

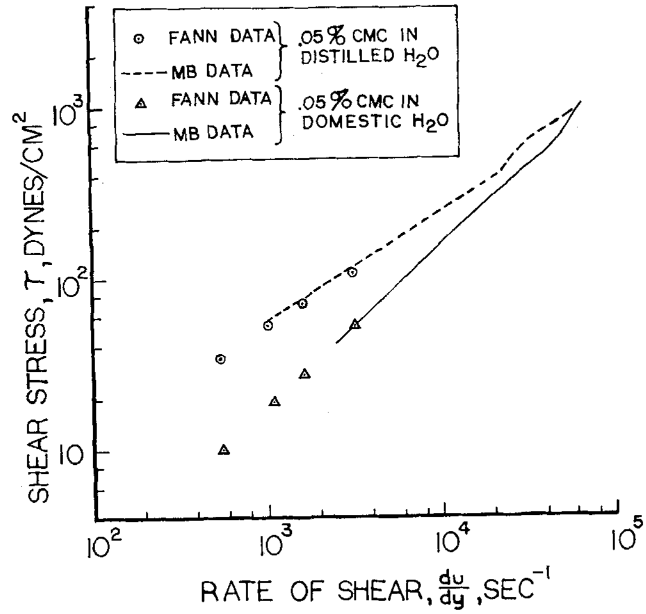

Fig. 1.

It was not the intention of these experiments to provide quantitative data that others might use in their own research, but only to show that greater care must be taken before accepting viscosity data in the literature when the solvent analysis was omitted or comparing flow data taken with like concentrations of the same fluid (*6*, *9*).

The fluids tested were 0.05% concentrations by weight of several polymer additives commonly used in basic research studies. The first is sodium carboxymethylcellulose (CMC 7HSP), which is essentially nonassociating, free draining, random coiling, and slightly anionic (*6*) in dilute solutions (less than 1%). Natrosol 250 (HHR) is a cellulose gum like the carboxymethylcellulose, but it differs in being nonionic and having a hydration inhibitor. The third polymer, J-2P, is basically a guar gum of galactomannan, consisting of a high molecular weight carbohydrate polymer having galactose branches. The solvents used were domestic water and high purity distilled water. No attempt was made to correlate the water properties with the observed effects. An analysis of each fluid solvent used is given in Table 1.

TABLE 1. WATER ANALYSIS

Test	Domestic, p.p.m.	Distilled, p.p.m.
Total dissolved solids	1135.5	0.9
Chlorides as Cl	87	trace
Sulfates as SO_4	310	trace
Iron as Fe	0.1	trace
Calcium as Ca	2.0	trace
Magnesium as Mg	2.4	trace
Sodium as Na	271	trace
Carbonates as CO_3	17	trace
Bicarbonates as HCO_3	445	trace
Fluorides as F	trace	trace
Metaphosphates as PO_3	1	trace
*p*H value	8.4	6.8
Total hardness	14.8	

EXPERIMENTS

For each fluid sample to be tested, both the solvent (water) and the polymer ad-

TABLE 2. POWER LAW CONSTANTS

Fluid	80°F.		95°F.	
	n	*a*	*n*	*a*
Distilled water	1.00	0.0085	1.00	0.0072
CMC domestic	0.87	0.050	0.84	0.056
CMC distilled	0.65	0.56	0.65	0.49
Nat domestic	0.89	0.040	0.91	0.030
Nat distilled	0.90	0.034	0.90	0.030
J-2P domestic	0.95	0.023	0.93	0.023
J-2P distilled	0.93	0.027	0.91	0.027

ditive were weighed to 0.1% accuracy after the moisture content of the additive had been accurately determined. The powder was dispersed in a vortex formed by agitating the water with a propeller mixer and allowed to dissolve at room temperature.

Two separate tests utilizing commercially available equipment were required to cover the shear rate range desired. The Fann Model 35 rotational viscometer was used to measure the shear stress at discrete shear rates below 3,300 sec.$^{-1}$, while the Merrill Brookfield High Shear Rate Viscometer was used in the shear stress range from 3,000 sec.$^{-1}$ to 70,000 sec.$^{-1}$.

In addition to measuring the final (after 24 hr.) viscosity, the Fann viscometer was used to determine the viscosity of each of the six solutions as a function of time.

Figure 1 demonstrates the marked dependence of the final viscosity of the CMC solution on solvent purity. Although the impurity content of the domestic water used for the tests was extremely high, there is every reason to believe that smaller amounts of impurities would still produce some deviation from the viscosity expected with the distilled water, not necessarily in proportion, however. The final viscosity of the other two additive solutions has relatively little dependence on the solvent purity, as shown in Table 2.

The effect of increased solvent purity on Natrosol was an increase in the time required for the solution viscosity to reach its steady state value. During this time the exponent *n* did not change, although the coefficient increased significantly. Fourteen minutes after mixing, the coefficient for the Natrosol distilled water solution was 88% of the final value, while the coefficient for the Natrosol domestic water solution was 98% of its final value. The steady state viscosity was reached after approximately 30 min. Neither CMC nor J-2P showed any significant difference in the time required for the viscosity to reach its final value. Of the three additives only J-2P had a viscosity independent of both time and solvent purity.

Tabulated in Table 2 are the power law constants *n* and *a* at 80° and 95°F. In every instance the effect of the additive is to alter the normal dependence of the viscosity of water on temperature.

The results of these simple experiments, shown in Figure 1 and Table 2, demonstrate that solvent purity is of considerable importance in determining the viscosity of non-Newtonian fluid solutions especially for anionic polymers. Once the rheological properties are completely defined and measured, a more realistic approach can be made to understanding the total effects of solvent purity on the rheology of an elasticoviscous fluid.

ACKNOWLEDGMENT

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Heat Transfer Efficiency in Rough Pipes at High Prandtl Number

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Recently, Dipprey (*1*) has suggested that heat transfer efficiency, defined by heat transmission per unit pressure drop, might be higher in rough tubes than in smooth ones for fluids with a high Prandtl number. If for these fluids the increase in efficiency is sufficiently large, the use of rough pipes for transferring heat becomes economically feasible.

To date very little data have been published for heat transfer in rough pipes for fluids with Prandtl number greater than 8, although many studies have been made in the field (*1* to *3*). Without exception previous results have shown that smooth pipes are more efficient than rough ones. Preliminary experimental results reported here, however, show a significant improvement in efficiency of heat transfer to a fluid having a Prandtl number of 349 over that obtained under similar flow conditions in a smooth tube.

EXPERIMENTAL

Three experimental test sections were used in the investigation, one being a smooth tube that was used for comparative purposes. The other two sections were roughened by internally threading two ⅜ in. I.D. brass pipes with specially made taps. The test section of the apparatus was electrically heated and the readings from the voltmeter and ammeter were used to determine the heat input. The wall temperatures were measured with four thermocouples embedded in the pipe, and the readings from them were recorded on a strip chart potentiometer. Water and Ucon, a polyalkylene glycol with a Prandtl number of 349, were used as the experimental fluids. The heat transfer coefficient and the friction factor were determined at various Reynold numbers for all three tubes from the pressure drop and temperature readings.