Studies of Drag Reduction Conducted over a Broad Range of Pipeline Conditions when Flowing Prudhoe Bay Crude Oil

E. D. BURGER, L. G. CHORN, and T. K. PERKINS, *ARCO Oil and Gas Company, Division of Atlantic Richfield Company, P.O. Box 2819, Dallas, Texas 75221*

Synopsis

The effects of solvent viscosity, bulk velocity, and pipe diameter on drag reduction have been investigated in order to ascertain the feasibility of utilizing polymer drag-reducing additives to increase the flow rate in the Trans-Alaska Pipeline. Laboratory screening studies were performed in 1- and 2-in. diam flow loops to determine the best commercially available additive for the application. Field tests in a 14-in. crude pipeline and in the 48-in. Trans-Alaska Pipeline confirmed the material's effectiveness in large-scale applications. This research program has resulted in the use of drag-reducing additive in the Trans-Alaska Pipeline as a temporary replacement for unconstructed pump stations.

The effect of additive concentration was investigated over a range of 5 to 25 ppm. The crude-oil flow conditions that were studied included solvent kinematic viscosities of 9 to 50 mm^2/sec (9 to 50 cs), Reynolds numbers of 4000 to 300000, wall shear rates of 100 to 2000 sec^{-1}, as well as inside pipe diameters from 2.66 to 119.4 cm (1.05 to 47.0 in.). The drag-reduction results have been correlated based on an extension of a theoretical model available in the literature. The functional form of the model requires a knowledge of the wall shear rate, the friction factor, and the additive concentration as independent variables.

INTRODUCTION

Opportunity for Application

Drag reduction with high-molecular-weight polymers is a broadly documented laboratory phenomenon.[1–6] Despite its obvious potential for utilization in industrial applications, many problems, including mechanical and/or chemical degradation of the polymer molecules and marginal economic incentives, have slowed its ex-

 Published by John Wiley & Sons, Inc.
Journal of Rheology, 24(5), 603–626 (1980) 0148-6055/80/0024-0603$02.40

ploitation. For many pipeline operations, increased throughput or pump station shutdowns can be dealt with economically by installation of higher capacity pumps or temporary portable pumping facilities; hence, the use of polymer drag reduction is usually not an optimal utilization of capital resources. This evaluation can change drastically for large-scale, high-volume pipelines in hostile environments, such as the Trans-Alaska Pipeline (TAPS), extending from Prudhoe Bay, Alaska, to Valdez, Alaska, a distance of 1287 km (800 miles).

At start-up, the TAPS crude oil flow rate was constrained to approximately 7420 m^3/hr (1.12×10^6 bbl/day) by pump volumetric capacity and pipe pressure limitations. By fine tuning the operation of the pipeline, Alyeska Pipeline Service Company was able to increase the flow rate by about 10%. Any further increase would require construction of intermediate pump stations at great cost. Utilization of polymer drag reduction becomes a viable alternative in situations where additional pump stations may only be required for several years or where pump stations cannot easily be constructed.

Scope of the Investigation

The research program leading to the application of a drag-reducing agent in TAPS was composed of three distinct areas of effort: laboratory screening of additive candidates, large-scale evaluation of additives, and correlation of the drag-reduction data for commercial utilization. The program was not designed to investigate the mechanism of polymer drag reduction but to apply state-of-the-art knowledge to select the most effective available additive for the application and to develop a reliable correlation for scaling drag reduction in crude oil pipelines.

The laboratory-scale phase of the program was designed to evaluate the drag-reduction effectiveness of various additives and their potential effects on refinery processing. The latter screening study evaluated the additives with respect to desalting, foaming, and thermal decomposition in addition to other properties pertinent to refinery operation.

One- and 2-in. nominal diameter test loops were used to perform the laboratory screening of the drag-reduction additives for their drag-reduction effectiveness. Since the effect of the solvent on drag reduction was not clearly understood, the experiments were per-

formed using Sadlerochit crude, the crude transported through the TAPS pipeline, at 60°C, the inlet temperature to TAPS. The test loops were designed to provide turbulent flow at bulk velocities comparable to those in the TAPS pipeline.

A total of nine potentially commercially available materials were investigated in the laboratory at concentrations that might have been economically feasible for commercial applications. These concentrations ranged from 5 to 50 ppm polymer. Two additives were selected for further testing. Most of the candidate additives did not provide acceptable levels of drag reduction while the others that were rejected were found to be unsuitable for refinery processing. The refinery processing studies were performed at an Atlantic Richfield research facility other than that at which the drag-reduction effectiveness of the additives was evaluated. No details of these processing studies will be presented, as the results are not pertinent to the investigation discussed in this paper.

The two remaining additives were subsequently tested in a 14-in. nominal diameter pipeline used to transport Sadlerochit crude oil in the continental United States. The effects of polymer concentration, bulk velocity, pipe diameter, and solvent viscosity were studied in this portion of the research program. In addition to demonstrating high levels of drag reduction in a commercial pipeline, the crude treated with additive was processed in a refinery with no detrimental effects being observed.

The results of the laboratory-scale and 14-in. pipeline experiments justified proceeding with further evaluation of Conoco Chemical Company's CDR* drag reducer in the TAPS pipeline. Separate injection tests were subsequently performed at two pump stations in order to study the effects of concentration, velocity, and viscosity on the effectiveness of the additive in the 48-in. pipeline. Problems concerning handling and injection of concentrated polymer solution at low temperature, pipeline control under drag-reduction conditions, and polymer degradation were all investigated during this portion of the study. The effects of refining large quantities of treated crude oil were also subsequently observed.

The drag-reduction data obtained in these studies have been used to evaluate several of the existing correlations available in the literature. The range of conditions of viscosity, concentration, pipe diameter, and turbulence properties provided a unique opportunity to

* CDR is a trademark of Conoco, Inc.

investigate the applicability of various scaling techniques. The bulk flow data obtained in these studies have indicated that a modification of the time scale hypothesis of turbulent flow field interaction with the polymer molecule is the most appealing, both for the understanding of the physics of the phenomenon and in providing a reliable prediction technique for commercial drag-reduction applications. Use of the correlation technique for prediction of required concentrations of additive to achieve a desired flow improvement in TAPS has met with remarkable success.

DESCRIPTION OF THE EXPERIMENTS

Laboratory Screening Apparatus

The laboratory test loop was designed to study the effectiveness of the various drag-reducing additives in Sadlerochit crude oil at oil temperatures up to 60°C. Since turbulent flow is necessary for drag reduction to occur, the system was designed for Reynolds numbers greater than 4000 at velocities comparable to those in TAPS.

Figure 1 shows the overall piping layout for the apparatus. All of the piping was standard Schedule 40 steel pipe. The test loops were traced with heat tape and insulated. The tanks held about 300 liter crude oil and were equipped with heaters and mixers. The pumps were positive displacement gear pumps. Pumps P1 and P2 were driven by constant rpm gear motors while the drive motors for pumps P3 and P4 were of manually controlled variable speed design. Validyne differential pressure transducers were used to measure pressure losses in the first half and also over the total length of each test loop. The crude oil flow rate was meaured with a Ramapo strain gauge flowmeter. Outputs of the pressure transducers and flowmeter were monitored directly on strip chart recorders during operation.

Prior to a test, the Sadlerochit crude oil was heated to 80°C under pressure in tank B1 or B2 for beneficiation, a process which redissolved precipitated waxy solids and eliminated the effects of prior temperature history of the crude. The oil was then cooled to the operating temperature of 60°C and transferred to the feed tank. The appropriate amount of drag-reduction additive was prepared for injection into the temperature-controlled feed tank by diluting with diesel oil. The prepared additive was injected into the feed tank using a slight nitrogen pressure. Typically, 2 hr of mixing in the tank with

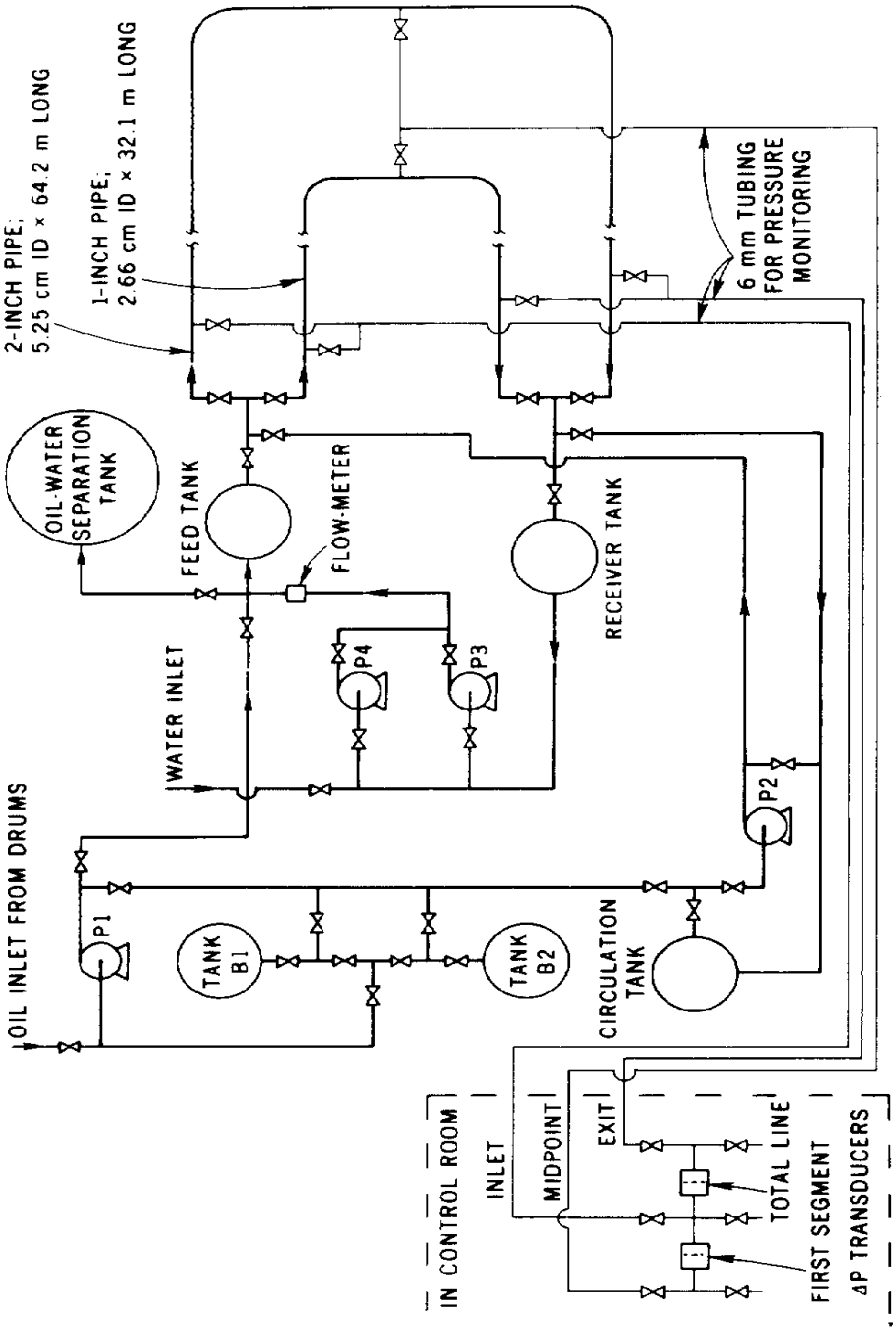

Fig. 1. Schematic diagram of laboratory drag-reduction test loop apparatus.

a 60 rpm stirrer were allowed prior to performing the test. The test loop to be used was stabilized at the operating temperature with heat trace tape and by pumping heated untreated crude from the circulating tank through the test loop. To avoid mechanical degradation of the polymer, the treated crude oil was not passed through a pump. The receiver tank was filled with tap water, and the water was pumped with P3 or P4, depending on the flow rate desired, into the bottom of the feed tank containing the crude oil. The treated crude was thus displaced through the flow loop and into the top of the receiver tank from which the water was being pumped. The water flow rate was set at a desired level, and when the pressure differentials in the test loop stabilized, the rate was changed. Depending on the test loop and the flow rate range studied, from one to six velocities could be run with one tank of crude oil. The test was terminated when the oil temperature at the test loop inlet began to drop. This indicated that the water–oil interface was approaching the top of the feed tank. The oil and water were later allowed to separate, and the oil was discarded.

Large-Scale Experiments

The drag-reduction effectiveness of two additives was studied in a 8.29 km (5.15 mile) section of a 14-in. nominal diameter pipeline used for transporting Sadlerochit crude oil. After obtaining calibration data for the untreated crude, concentrated additive was injected into the flowing crude at a specified rate in order to obtain a complete line fill at a constant additive concentration. The oil flow rate was maintained constant during this period. After obtaining a stabilized pressure drop reading, the oil flow rate was varied. The additive injection rate was also changed in order to maintain the same concentration in the pipeline. This procedure continued until a complete velocity traverse was made. Several additive concentrations were evaluated in this manner. The line pressures were monitored with Heise gauges and Viatran transducers. The additive injection rate was measured with a Brooks Oval Flowmeter, while the crude oil flow rate was monitored by the pipeline's A. O. Smith positive displacement meter.

Two drag-reduction experiments were run during April and May of 1979 in the 48-in. nominal diameter TAPS pipeline utilizing the Conoco CDR drag-reducing additive. These experiments took place

first in the 167 km (104 mile) segment between pump stations 1 and 3 and subsequently in the 216 km (134 mile) segment between pump stations 6 and 8. Neither pump station 2 nor 7 was in operation at the time of the experiments. The additive was injected into the pipeline with a low rpm gear pump on the discharge side of the main line pumps at pump station 1 or 6 during constant oil flow rate conditions. Pressure monitoring sites were maintained at pump stations 1, 2, and 3 for the first experiment and at pump stations 6, 7, and 8 for the second. To ensure accuracy of the measurements, three pressure-measuring devices were used at each site: Ametek dead weight testers, Heise pressure gauges, and Stathem pressure transmitters. The concentrated additive was injected with gear pumps to minimize mechanical degradation. A Fluidyne helix positive displacement flow transducer was used to monitor the additive injection rate. The pipeline flow rate was obtained at 15 min intervals to ensure a constant concentration of additive in the pipeline. In addition to measuring the drag reduction at three additive concentrations in each line segment, a short duration flow improvement experiment was run during the pump station 1 injection period.

Experimental Materials

The solvent for the tests was Sadlerochit crude oil, the oil produced at Prudhoe Bay and transported to Valdez in the TAPS pipeline. General characteristics show that it is an intermediate gravity (about 27°API or 0.893 g/cm^3 at 15.6°C), high sulfur (about 0.8%), high nitrogen (about 0.2%) oil.[7] It is naphthenic, aromatic, waxy, and has a pour point of about −5°C.

The drag-reduction results that are reported were obtained by using the CDR drag-reduction additive. This material is a polymerized straight-chained α-olefin monomer of one or more pure hydrocarbons above six carbon atoms.[8] It was supplied as a 10 to 11% by weight solution in a hydrocarbon solvent.

EXPERIMENTAL RESULTS

Pipeline Calibration

Drag reduction is defined as

$$\% \text{ drag reduction} = [(\Delta P_0 - \Delta P_p)/\Delta P_0] \times 100 \quad (1)$$

where ΔP_0 is the friction pressure drop for untreated fluid and ΔP_p is the friction pressure drop for treated fluid, both measured at the same volumetric flow rate. Calibration of each pipeline and laboratory test loop was performed with untreated crude oil prior to testing any drag-reduction additives.

Figure 2 shows the calibration pressure drop data for the two laboratory test loops, while Fig. 3 summarizes the calibration data obtained for the 14-in. pipeline for the two separate series of experiments utilizing CDR drag reducer. The laboratory data were obtained at 60°C as compared to 14 and 19°C for the pipeline tests.

The TAPS drag-reduction experiments were performed at a constant flow rate of about 8015 m^3/hr (1.21×10^6 bbl/day), the pipeline's approximate capacity at non-drag-reduced conditions. The crude oil pressure drop was monitored continuously in each pipeline seg-

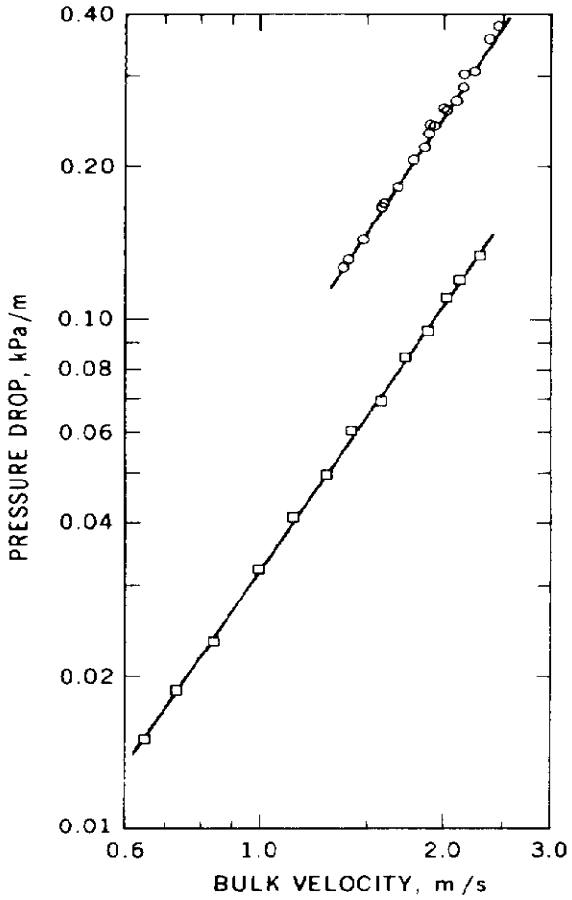

Fig. 2. Laboratory test loop calibration data. (○) 1-in. pipe; (□) 2-in. pipe.

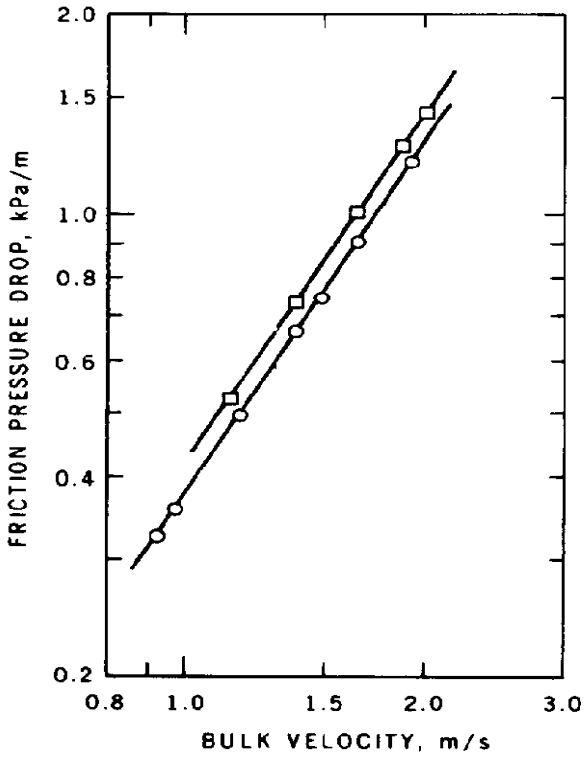

Fig. 3. Fourteen-in. pipeline calibration data. (□) 14°C; (○) 19°C.

ment being studied for an extended interval prior to each experiment in order to obtain the necessary calibration data. The untreated crude pressure drop to be expected at the higher flow rate conditions during the flow improvement test between pump stations 1 and 3 was calculated based on the pressure drop data taken at the lower base flow rate of 8015 m^3/hr.

Drag-Reduction Measurements

The drag-reduction experiments were performed typically at nominal polymer concentrations of 5, 10, and 20 ppm by weight. The results of the calibration runs with untreated crude and of the 20 ppm experiments, expressed in terms of the measured Moody friction factor, are presented in Fig. 4. The Reynolds number variation for the 1- and 2-in. and each 14-in. data set reflect only the effect of velocity since each of these experimental series was performed at constant temperature. The three 48 in. pipeline data points represent the effect of viscosity variation.

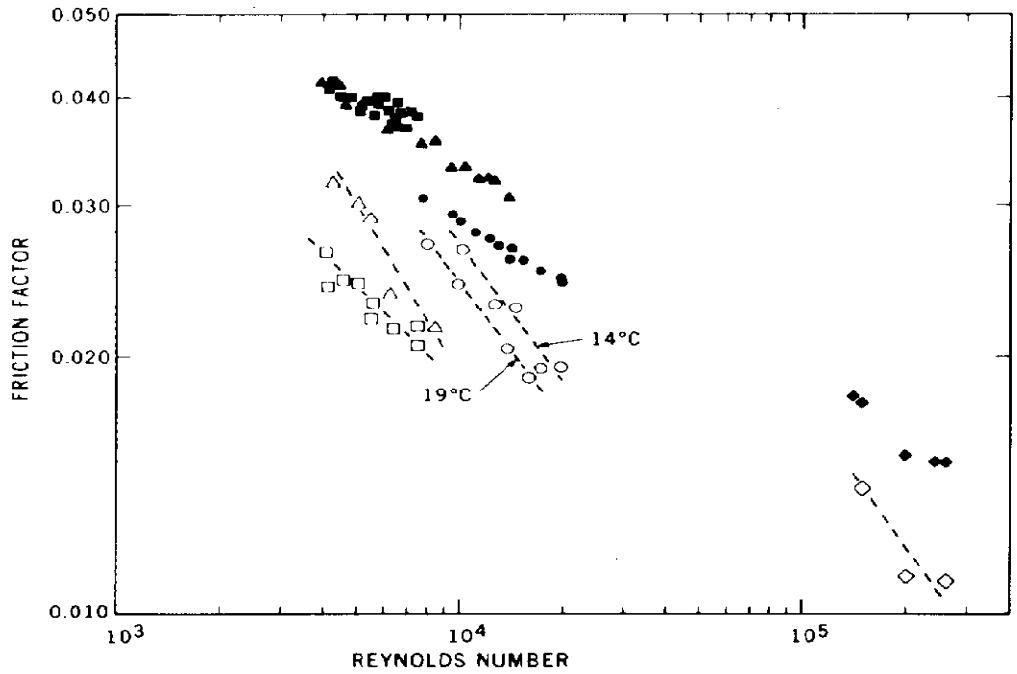

Fig. 4. Measured friction factors for 20 ppm CDR in Sadlerochit crude oil and for untreated crude. Solid symbols are calibration data for untreated fluid; open symbols are for 20 ppm CDR. Nominal pipe size (in.): (■□) 1; (▲△) 2; (●○) 14; (◆◇) 48.

The effect of additive concentration on drag reduction is shown in Fig. 5 for the TAPS experiments. The data represent drag reduction measured at equivalent bulk oil velocities. The two data sets indicate the effect of viscosity on the drag-reduction level. A flow improvement experiment was performed between pump stations 1 and 3 while the pipeline segment was filled with 10 ppm additive. By maintaining the pressure drop equivalent to that observed for untreated crude at the baseline flow rate, the flow rate was increased by an average of 14.4%. This corresponded to a drag-reduction level of 21 to 22%. About 19% drag reduction was obtained with a 10 ppm additive concentration in this line segment at 8015 m^3/hr.

During each TAPS experiment the pressure drop was also monitored in the pipeline segment downstream of pump station 3 (for the first experiment) and pump station 8 (for the second). These pressure drop data indicated that no residual additive effectiveness remained after the additive passed through a main line pump (at pump stations 3 and 8).

Table I summarizes the conditions and results for each of the 60

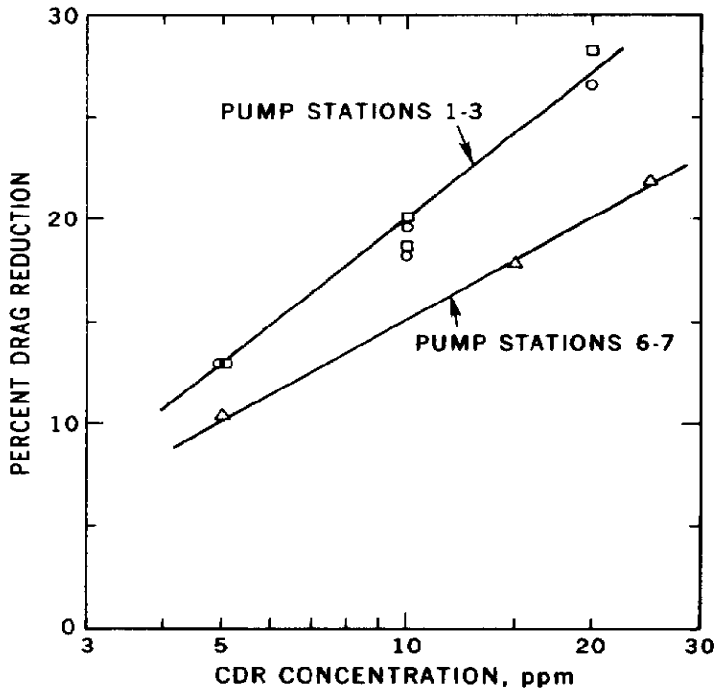

Fig. 5. Measured drag-reduction levels in the Trans-Alaska Pipeline. Pump station segment: (○) 1–2; (□) 2–3; (△) 6–7.

experiments run with the Sadlerochit crude oil/CDR drag-reducer system. Note that the 10 and 20 ppm results for the low-temperature TAPS experiments were obtained by interpolating the 5, 15, and 25 ppm results presented in Fig. 5.

SCALING OF BULK FLOW DATA

Previous Work

Although a significant amount of drag-reduction data has been generated, the controversy concerning the interaction of the turbulent flow field and the individual polymer molecules is not resolved. Early investigators[1] suggested that the onset of drag reduction for a given polymer–solvent combination is determined by a characteristic onset wall shear stress. Extending such a correlation to explain turbulent flow field–polymer molecular interactions leads to a length scale interaction hypothesis. That is, a length scale rationale is proposed such that at the onset of drag reduction a length scale of the turbulence, perhaps a particular eddy size, is of similar magnitude as a

TABLE I
Drag-Reduction Experimental Data

ϕ (ppm)	D (cm)	ν (mm^2/sec)	U_b (m/sec)	Re	f	% DR
5	2.664	8.42	2.417	7651	0.02778	27.00
	2.664	8.42	1.362	4313	0.03267	22.10
	2.664	8.42	1.804	5712	0.03045	22.90
	34.3	33.00	1.926	20024	0.02249	8.00
	34.3	33.00	1.430	14859	0.02495	4.90
	34.3	33.00	0.936	9727	0.02890	0.0
	34.3	33.00	1.207	12546	0.02567	5.70
	34.3	33.00	1.661	17267	0.02295	9.30
	119.4	9.20	2.051	266236	0.01297	12.95
	119.4	12.00	2.035	202567	0.01340	13.00
	119.4	16.20	2.042	150567	0.01573	10.40
10	5.250	8.67	0.707	4284	0.03508	16.20
	5.250	8.67	1.408	8530	0.02418	30.00
	5.250	8.67	0.875	5299	0.03277	15.00
	2.664	8.80	1.878	5687	0.02606	33.60
	2.664	8.80	2.512	7607	0.02458	35.20
	2.664	8.80	1.359	4118	0.02972	28.90
	2.664	8.80	1.585	4801	0.02821	30.10
	34.3	33.00	1.929	20055	0.02105	13.80
	34.3	33.00	1.423	14796	0.02363	9.70
	34.3	33.00	1.237	12863	0.02483	8.20
	34.3	33.00	0.994	10329	0.02683	6.00
	34.3	33.00	1.676	17426	0.02103	16.50
	34.3	50.00	2.015	13822	0.02223	14.80
	34.3	50.00	1.692	11605	0.02419	11.80
	119.4	9.20	2.051	266236	0.01196	19.70
	119.4	9.20	2.051	266236	0.01218	18.20
	119.4	12.00	2.035	202567	0.01231	20.10
	119.4	12.00	2.035	202567	0.01253	18.70
	119.4	16.20	2.042	150567	0.01492	15.00
	119.4	12.00	2.342	233052	0.01158	23.10
	119.4	9.20	2.345	304377	0.01145	21.20
	119.4	12.00	2.322	231050	0.01183	21.60
	119.4	10.00	2.333	278644	0.01161	21.40
20	5.250	8.67	0.914	5539	0.02875	23.90
	5.250	8.67	1.036	6278	0.02359	35.60
	5.250	8.67	0.713	4321	0.03193	23.30
	5.250	8.67	0.847	5133	0.03022	23.00
	5.250	8.67	1.408	8530	0.02162	37.40
	2.664	8.80	2.496	7561	0.02054	45.80
	2.664	8.80	1.375	4164	0.02412	42.30
	2.664	8.80	1.832	5548	0.02206	44.00

TABLE I (*Continued from previous page.*)

ϕ (ppm)	D (cm)	ν (mm^2/sec)	U_b (m/sec)	Re	f	% DR
	2.664	8.80	2.134	6462	0.02150	44.20
	2.664	8.93	1.878	5604	0.02315	41.00
	2.664	8.93	2.536	7569	0.02174	42.50
	2.664	8.93	1.359	4058	0.02636	36.90
	2.664	8.93	1.533	4576	0.02464	39.40
	2.664	8.93	1.692	5049	0.02438	38.90
	34.3	33.00	1.917	19929	0.01948	20.20
	34.3	33.00	1.414	14701	0.02278	13.30
	34.3	33.00	0.985	10234	0.02656	7.10
	34.3	33.00	1.234	12832	0.02303	15.10
	34.4	33.00	1.655	17204	0.01941	23.40
	34.3	50.00	2.012	13801	0.02043	21.90
	34.3	50.00	1.451	9954	0.02433	14.90
	34.3	50.00	1.173	8051	0.02700	11.00
	34.3	50.00	2.304	15809	0.01895	24.70
	119.4	9.20	2.051	266236	0.01093	26.60
	119.4	12.00	2.035	202567	0.01105	28.30
	119.4	16.20	2.042	150567	0.01404	20.00

characteristic length of the polymer molecule, be it the chain length of a partially extended molecule or the radius of gyration. Lumley,[2] however, has shown that the shortest dynamically significant length in turbulent flow, at the onset of drag reduction, is of the order of 10^3 times the size of the radius of gyration of the polymer molecule. Reviewing recent Newtonian turbulence investigations of the characteristics of bursts, a dramatic near-wall phenomenon felt to be involved in the generation of turbulent energy, Virk[9] has indicated that a fully uncoiled polymer molecule is approximately the length of a burst microscale. However, he adds that no experimental evidence exists to indicate that a molecule can attain such a state. Although experimental data are strongly supportive of the length scale hypothesis, experience with non-drag-reduced flows tends to diminish the acceptance of this rationale. Lumley[2,10] and Landahl[11,12] have proposed a molecular elongation phenomenon. Such an extension should result in extremely large elongational viscosities which may cause a reduction in the turbulent energy production.

Another approach to correlating drag reduction with turbulent bulk flow parameters is the time scale hypothesis. Lumley[2] has calculated that the characteristic time scale of the turbulent flow field, ν/U^{*2},

is of the order of the molecular relaxation time of a monodisperse polymer sample. Berman and George[3] investigated the time scale hypothesis experimentally in regard to the onset of drag reduction. Their results support the contention that the onset of drag reduction is related to a time frame interaction of the turbulence with the polymer molecules. However, the use of a polydisperse polymer sample clouded the results. Berman and George indicated that the relaxation times of a polydisperse polymer sample should be described by a distribution function rather than a single value. Consequently, by increasing the characteristic time of the turbulence, more of the distribution of relaxation times would be affected, thus increasing the drag reduction. Chorn[4] used this approach to increase the level of drag reduction for a given polymer concentration in a 2.60 cm pipe by increasing the solvent viscosity and hence the value of ν/U^{*2} for a given Reynolds number.

Several experimental studies of the drag-reduced turbulent flow field have also evaluated scaling techniques. Since the effect of drag-reducing polymers is felt only when the molecules are in the near-wall region of the flow field, research has focused here. Several investigations[5,6,13] have measured axial and transverse length scales of the near-wall region and found them to be significantly increased with drag reduction. Scaling with the characteristic length, ν/U^*, leads to a monotonic increase in length with increasing drag reduction. The turbulent energy spectrum of axial fluctuations near the wall during drag reduction also shows significant changes from the non-drag-reduced spectrum. However, when scaled with the characteristic time scale of the turbulence, ν/U^{*2} ($= \gamma^{-1}$, sec) near the wall, the spectra of drag-reduced flows closely resemble the non-drag-reduced spectrum. This indicates that the effect of the polymer molecules on the near-wall velocity fluctuations is related to the time scale of each. Although conclusive evidence is lacking, a time frame interaction phenomenon is the most pleasing to the intuitive analysis of the physics of drag reduction.

Scaling of the Present Data

In order to predict the expected levels of drag reduction in the 14- and 48-in. diam pipe experiments, based on laboratory-scale tests, various correlation techniques were investigated. The correlation of previous investigators using Conoco CDR drag reducer[14] did not

adequately predict the effectiveness of the additive in the range of flow conditions studied. This was due, in part, to the different solvent and the improved quality of the additive. The length and time scale hypotheses were then examined to determine their utility in the prediction of drag-reduction levels.

The correlation of the data using the length scale hypothesis is presented in Fig. 6. This represents an attempt to correlate the magnitude of drag reduction with the turbulent length scale, ν/U^*. For a given pipe diameter the relationship of percent drag reduction

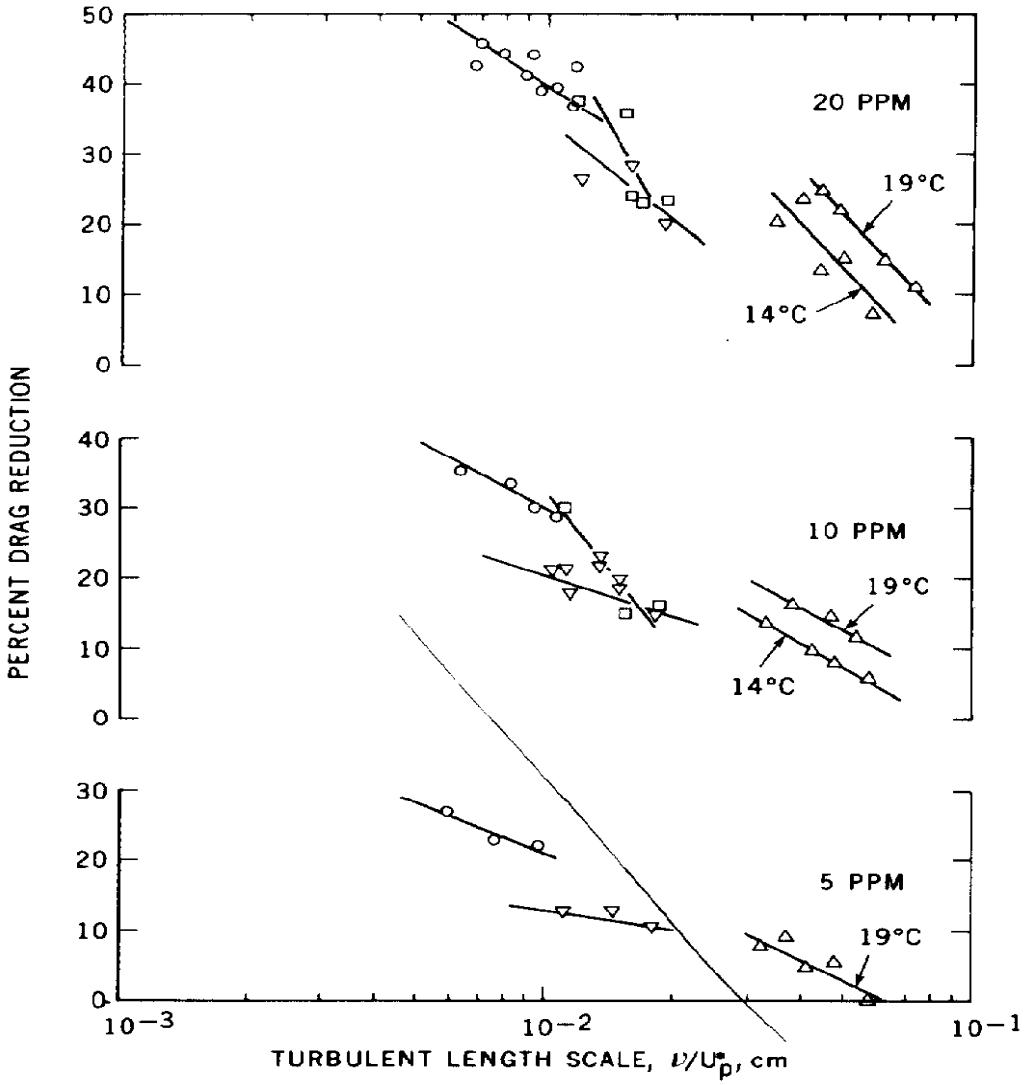

Fig. 6. Correlation of percent drag reduction with the turbulent length scale. Nominal pipe size (in.): (○) 1; (□) 2; (△) 14; (▽) 48.

to ν/U^* is approximately linear. However, each pipe diameter appears to be correlated with a line of unique slope and intercept. In addition, the two distinct lines through the 14-in. pipeline data for both the 10 and 20 ppm experiments indicate that the length scale does not properly account for viscosity effects. In light of these data, this scaling function does not appear viable as a technique to scale drag reduction. The magnitude of the drag reduction is plotted versus the turbulent time scale of the flow in Fig. 7. There is a considerable amount of scatter in the data for 1-, 2-, and 14-in. diam pipe flows, but an improvement in correlating the data compared to the

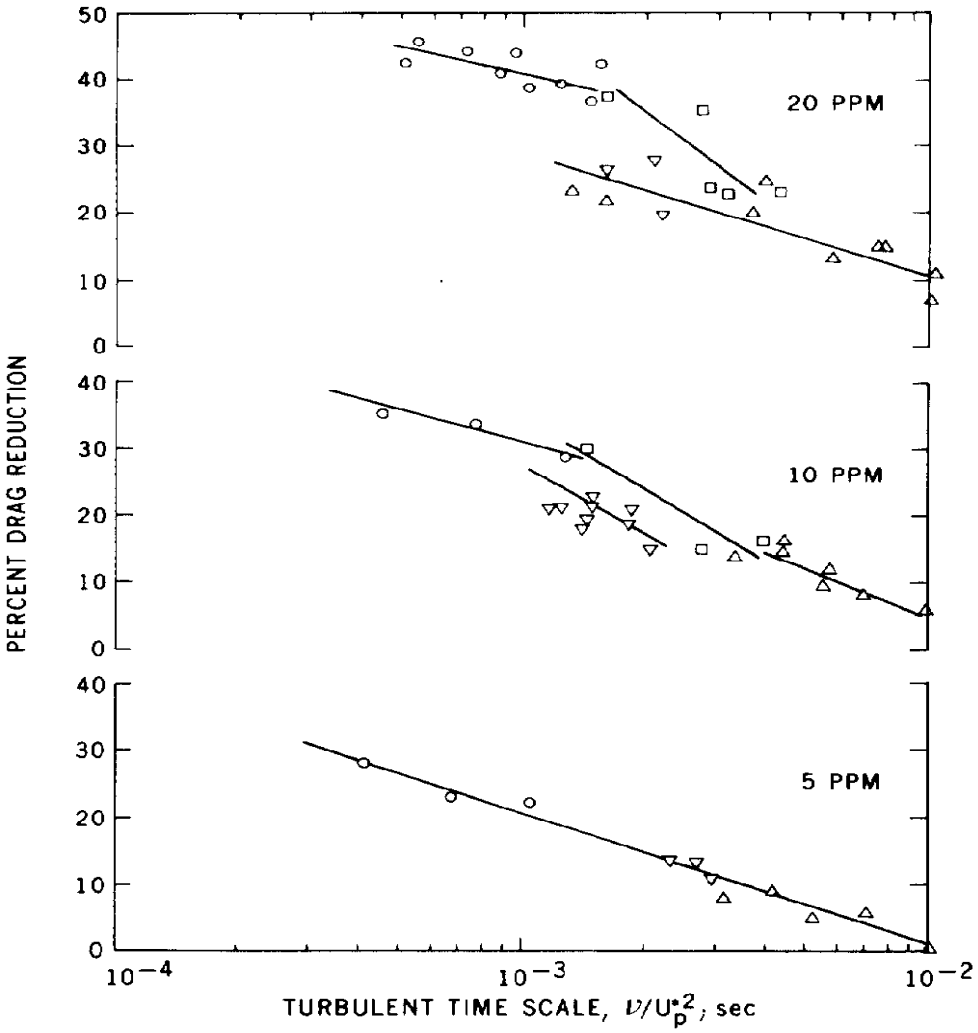

Fig. 7. Correlation of percent drag reduction with turbulent time scale. Symbols are the same as in Fig. 6.

turbulent length scale is noted. For example, the effect of viscosity in the 14-in. pipeline data appears to be better accounted for with this scaling hypothesis as compared to the length scale attempt, as shown in Fig. 6. However, the 48-in. diam pipe data are clearly not well predicted by the turbulent time scale. This suggests that, although the time scale hypothesis appears to be an improvement over the length scale hypothesis, the relationship of drag reduction to turbulent flow parameters is not a pure function of the time scale. An evaluation of the time and length scale hypotheses in correlating the onset of drag reduction was also attempted. However, the variation of solvent viscosity for a data set as well as the data scatter made the results difficult to interpret.

For the application of drag reduction to an industrial-scale project, the ability to predict the effect of drag reduction polymers and to design an injection system to achieve the desired effect is of primary importance. The requirement, therefore, is to define the proper parameters and to develop a scaling correlation relating flow conditions, polymer concentration, and drag-reduction levels for as great a variety of conditions as possible. The ability of the time scale hypothesis to outperform the length scale hypothesis in predicting the percent drag reduction leads to further investigation into utilization of some form of the time scale interaction for prediction.

The drag-reduction data accumulated with CDR™ drag reducer in Sadlerochit crude have been found to correlate well with two parameters which describe the flow in a pipeline. This correlation has been based on a model of turbulent viscoelastic flow presented recently by Savins and Seyer.[15]

According to this correlation, the fractional drag reduction, δ, is given by a relation of the form

$$\delta = 1 - 1/(1 + \alpha H)^2, \tag{2}$$

where

$$H = 2^{3/2} \log_{10} \sigma + 1.454 t_0 \sigma - 0.8809 - 2^{5/2} \log_{10} \beta, \tag{3}$$

$$t_0 = (U_0^*)^2 \theta_p / \nu_p, \tag{4}$$

$$\beta = \nu_p / \nu_0, \tag{5}$$

$$\alpha = U_0^* / U_b, \tag{6}$$

and the "drag ratio" is defined as

$$\sigma = (U_p^* / U_0^*)^2 = 1 - \delta. \tag{7}$$

Since $\nu_p \simeq \nu_0$ for low additive concentrations, then $\beta = 1.0$, and the characteristic time can be rewritten

$$t_0 = \gamma_0 \theta_p. \tag{8}$$

Equation (3) therefore simplifies to

$$H = 2^{3/2} \log_{10} \sigma + 1.454 \gamma_0 \theta_p \sigma - 0.8809. \tag{9}$$

Combining Eq. (9) with Eqs. (2) and (7) yields

$$\sigma[1 + \alpha(2^{3/2} \log_{10} \sigma + 1.454 \gamma_0 \theta_p \sigma - 0.8809)]^2 = 1. \tag{10}$$

The drag ratio is now a function of two flow parameters, α and γ_0, and one polymer–solvent parameter, θ_p.

The drag-reduction data were analyzed with Eq. (10) to determine the relationship for the characteristic time, θ_p, with the flow parameters. The characteristic time was found to relate to the drag-reduced shear rate, γ_p, and the additive concentration, ϕ, in ppm as follows:

$$\theta_p = a \phi^b \gamma_p^c. \tag{11}$$

The constants a, b, and c were found by linear regression to be 0.0516, 0.489, and −0.579, respectively. Figure 8 summarizes the comparison of the measured values of θ_p with those calculated by Eq. (11). Since $\gamma_p = \gamma_0 \sigma$, Eq. (11) becomes

$$\theta_p = a \phi^b (\gamma_0 \sigma)^c, \tag{12}$$

and now Eq. (10) can be expressed in terms of only σ, α, γ_0, and ϕ. For any given system for CDR drag reducer in Sadlerochit crude, ϕ, α, and γ_0 are well defined, and therefore the drag-reduction level can be determined.

Figure 9 summarizes the comparison of measured and predicted [from Eqs. (10) and (12)] percent drag reduction for each experiment. These experiments represent concentrations of 5 to 20 ppm, oil viscosities of 9 to 50 mm^2/sec (9 to 50 cs), inside pipe diameters of 2.66 to 119.4 cm (1.05 to 47.0 in.), bulk oil velocities of 0.6 to 2.4 m/sec (2 to 8 ft/sec), and Reynolds numbers of 4000 to 300000. The standard deviation for the relationship presented in Fig. 9 is 2.74% drag reduction.

It can be shown that

$$\alpha = (f_0/8)^{1/2}, \tag{13}$$

where f_0 is the Moody friction factor for the non-drag-reduced system.

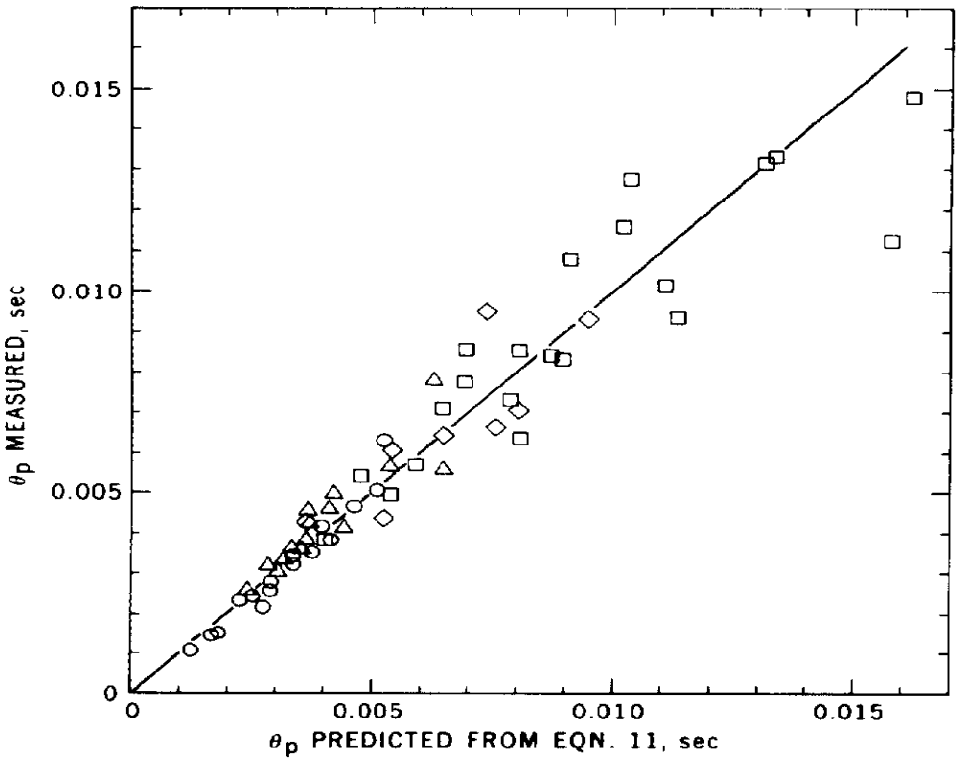

Fig. 8. Comparison of measured and predicted polymer characteristic times. Nominal pipe size (in.): (○) 1; (◇) 2; (□) 14; (△) 48.

For pipelines limited to a small range of Reynolds numbers, the value of α is therefore relatively constant, and the drag-reduction scaling factor for such a pipeline is only the wall shear rate. Figure 10 summarizes the calculated drag-reduction–shear rate relationships for the three pipeline systems studied in addition to the measured drag-reduction levels. In order to be in a form more useful for predictive purposes, the data are presented in terms of the non-drag-reduced shear rate.

For the onset of drag reduction, Eq. (10) reduces to

$$\gamma_0 \theta_p = 0.6058. \tag{14}$$

The constants in Eq. (11) have been determined according to the above relationship. Since θ_p is a function of both the additive concentration and the shear rate at the wall, the onset shear rate is concentration dependent. The calculated onset shear rate–concentration relationship for the system studied is summarized in Table II.

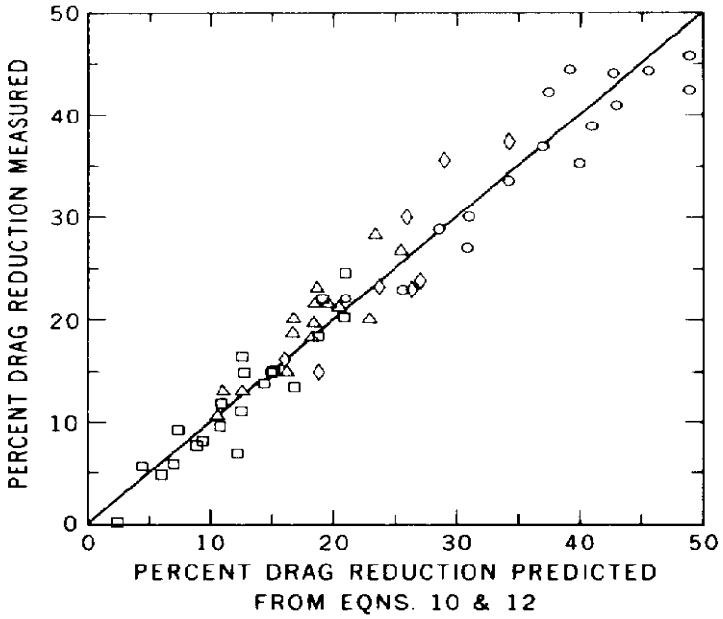

Fig. 9. Comparison of measured and predicted drag-reduction levels. Symbols are the same as in Fig. 8.

Application to Other Solvents

Additional drag-reduction experiments have been performed in the laboratory in order to evaluate the correlation for drag reduction in solvents other than Sadlerochit crude. Diesel was investigated in the 1-in. test loop and in a 1.99 cm (0.785 in.) i.d. test loop constructed especially for the study of low-viscosity fluids at ambient temperature. As illustrated in Fig. 11, the CDR's effectiveness in diesel was comparable to that in the Sadlerochit crude for shear rates greater than about 700 sec^{-1}. Drag-reduction levels for solutions of CDR drag reducer in heptane and toluene were measured in a 1.09 cm (0.43 in.) i.d. test loop. As shown in the figure, the additive was significantly less effective in these solvents. A 50% by volume mixture of diesel in heptane resulted in a drag-reduction level between those measured

TABLE II

Concentration (ppm)	Onset shear rate (sec^{-1})
5	54
10	24
20	11

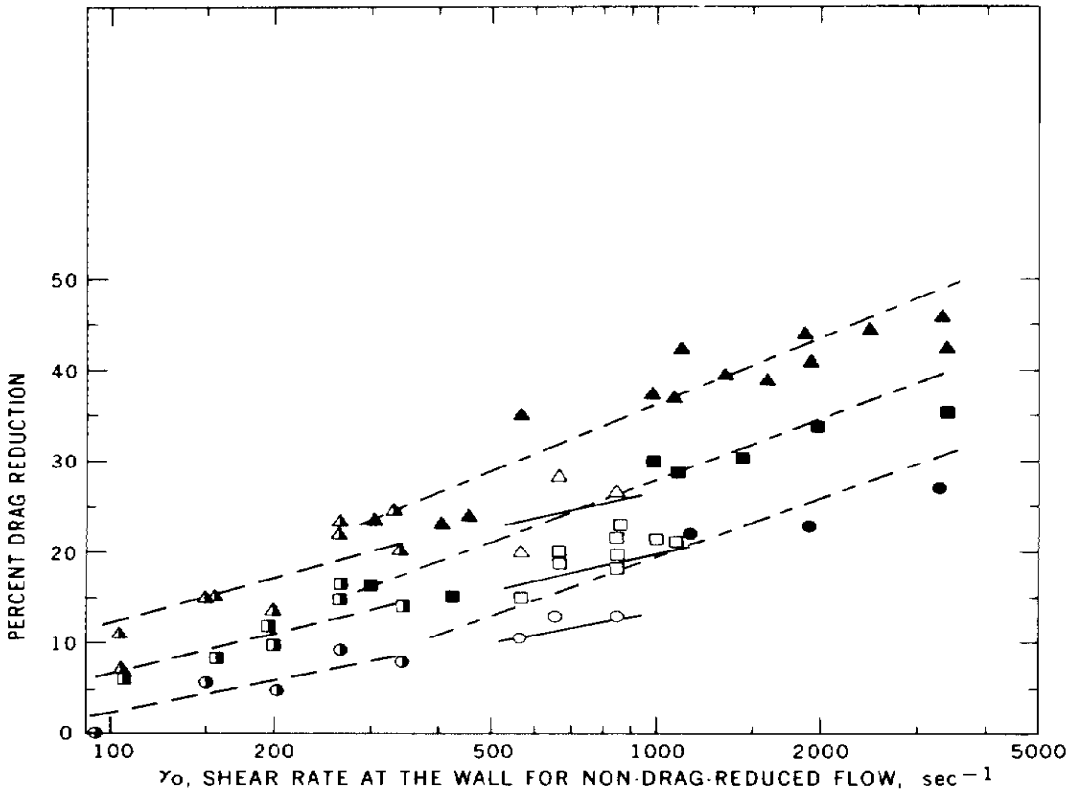

Fig. 10. Relationship between drag reduction and wall shear rate for different pipelines—CDR/Sadlerochit crude system. Pipe size = 1- and 2-in.: (———) Computed; (●,■,▲) measured, (●) 5 ppm; (■) 10 ppm; (▲) 20 ppm. 14-in. pipe size: (- - -) Computed; (◑,◨,◭) measured, (◑) 5 ppm; (◨) 10 ppm; (◭) 20 ppm. 48-in. pipe size: (——) Computed; (○,□,△) measured, (○) 5 ppm; (□) 10 ppm; (△) 20 ppm.

in the pure solvents. The heptane and toluene experiments were run at Reynolds numbers between 4000 and 8000, while the diesel heptane and diesel (in the 1.99 cm tube) were run at Re = 4500. The 1-in. test loop diesel tests encompassed Reynolds numbers from 5000 to 19000.

The results of these low-viscosity solvent experiments indicate that the empirical constants in Eq. (11) are unique to the polymer–solvent combination for which they were developed.

CONCLUSIONS

This study represents the preliminary investigation for the first commercial application of drag-reducing polymers in a large-scale pipeline. A wide range of flow conditions was investigated with the

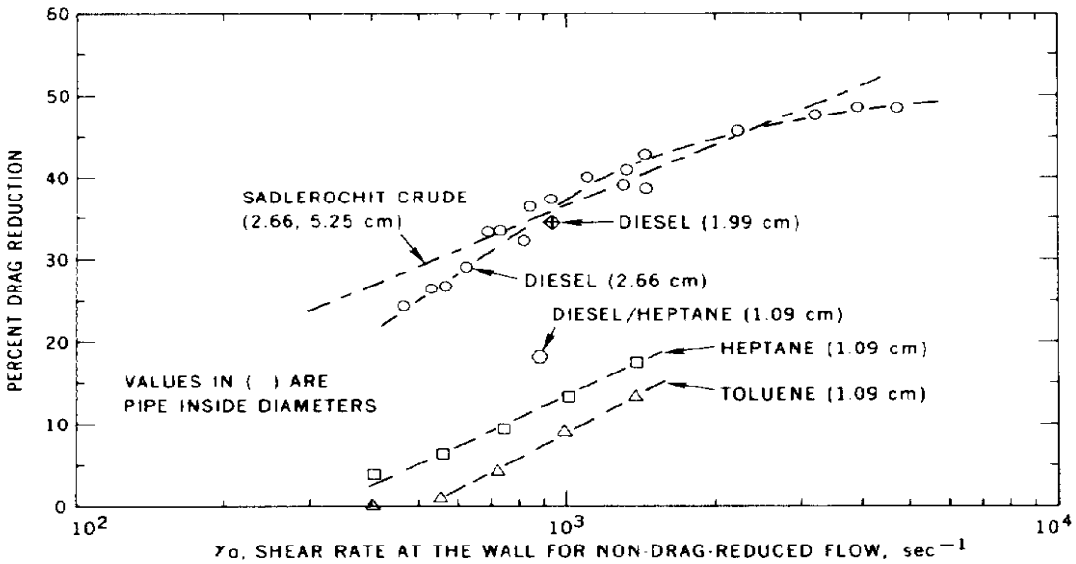

Fig. 11. Effect of solvent on drag reduction (20 ppm CDR additive). Values in parentheses are pipe inside diameters.

polymer–solvent combination for correlation of the data for predictive purposes. The data provide a unique test of several scaling theories and indicate an appropriate one.

Neither the time nor length scale hypotheses, *per se*, were found to adequately correlate the levels of drag reduction observed. However, an extension of the time scale model suggested by Savins and Seyers provides excellent scaling of drag reduction over a wide range of conditions. In this correlation, drag reduction is a function only of the polymer concentration, the shear rate at the wall, and the friction factor. For pipelines which are limited to a small range of Reynolds numbers, the friction factor dependency becomes insignificant.

Drag-reduction data for specific polymer–solvent systems must be correlated separately due to potential differences in the interactions of the polymer and solvent. Laboratory data can now be used to predict drag-reduction levels in large-diameter pipelines for the same polymer–solvent system.

Polymer drag reduction has been demonstrated to be a technologically feasible application for the Trans-Alaska Pipeline. It is presently being implemented in this pipeline to increase the crude-oil flow rate. The results are being carefully evaluated in order to de-

termine the economic efficiency and the effects on downstream refinery processing.

Nomenclature

D pipe diameter
f Moody friction factor
H defined by Eq. (3)
Re Reynolds number
t_0 dimensionless characteristic time, defined by Eq. (4)
U_b bulk velocity
U^* friction or shear velocity $[= (\tau_w/\rho)^{1/2}]$
α defined by Eq. (6)
β viscosity ratio, defined by Eq. (5)
γ shear rate at the wall $(= U^{*2}/\nu)$
ΔP friction pressure drop
δ fractional drag reduction
θ_p characteristic time
ν kinematic viscosity
ρ fluid density
σ drag ratio, defined by Eq. (7)
τ_w wall shear stress
ϕ additive concentration

Subscripts

0 non-drag-reduced system
p drag-reduced system

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Received November 1, 1979
Accepted as revised March 13, 1980