UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 71

Non-Newtonian Pipe Friction Studies with Various Dilute Polymer Water Solutions

by
JOHN F. RIPKEN
and
MEIR PILCH

Prepared for
DAVID TAYLOR MODEL BASIN
Department of the Navy
Washington, D.C.
under
Bureau of Ships General Hydromechanics Research Program
S-R009-01-01
Office of Naval Research Contract Nonr 710(49)

June 1964
Minneapolis, Minnesota

[illegible]

[illegible]

[illegible]

Reproduction in whole or in part is permitted
for any purpose of the United States Government

[illegible]

[illegible]

PREFACE

The evaluation studies described herein were designed to aid in clarification of the use of water soluble long-chain polymer additives as friction reducing agents for application to naval drag reduction problems.

The tests discussed in this report were undertaken in the facilities of the St. Anthony Falls Hydraulic Laboratory during the period from August 1963 to May 1964 and were sponsored under the Bureau of Ships, General Hydromechanics Research Program of the United States Department of Navy. The program was administered by the David Taylor Model Basin and the Office of Naval Research under Contract Nonr 710(49).

The authors wish to express appreciation to Paul G. Neuman and Fred J. Gientke for their considerable assistance and to the additive suppliers for the samples and descriptive pamphlets.

ABSTRACT

This study extends existing data on the frictional drag reducing influence of long-chain polymers in dilute water solutions. Studies were conducted with both fresh and sea water in capillary tubes and pipes with a size range of 100 diameters and covering the laminar, transition, and turbulent regimes with N'_{Re} up to 8×10^5. Fifteen types of test additives were used, including Polyhall, Polyox, Westco Guar, and fish slime. Test temperatures ranged from 40° to 85° F.

Dilute solutions ranging down to 10 ppm concentration exhibited remarkable friction reductions at high shear rates as a near-laminar type of flow. Data correlation was hampered by diameter, temperature, and concentration effects not resolved by existing flow parameters based on power law theory.

Shear degradation effects were evaluated.

CONTENTS

LIST OF SYMBOLS

dv/dr - shear rate, sec^{-1}

$(dv/dr)_w$ - shear rate at a wall, sec^{-1}

D - pipe or tube diameter, feet

$D\Delta P/4L$ or τ_w - unit shear stress at the wall of a pipe or tube, lb force/sq ft

f - Fanning friction factor, dimensionless

g - gravitational constant

K - consistency index as defined by Eq. (6), (lb force)(sec^n)/sq ft

K' - consistency index as defined by Eq. (9), (lb force)($sec^{n'}$)/sq ft

L - length between measuring stations of pipe or tube, feet

n - flow behavior index as defined by Eq. (6), dimensionless

n' - flow behavior index as defined by Eq. (8), dimensionless

N_{Re} - Reynolds number for Newtonian fluids, dimensionless

N'_{Re} - Reynolds number as defined by Eqs. (12) or (13), dimensionless

ΔP - pressure drop, lb force/sq ft

r - radial distance, feet

V - average velocity, ft/sec

$8V/D$ - shear rate of a Newtonian fluid at the wall of a pipe or tube for laminar flow conditions, sec^{-1}

μ - viscosity of a Newtonian fluid, lb mass/(sec)(ft)

ρ - fluid density, slugs/cu ft

τ - unit shear stress, lb force/sq ft

LIST OF ILLUSTRATIONS

Figures Page

NON-NEWTONIAN PIPE FRICTION STUDIES WITH VARIOUS DILUTE POLYMER WATER SOLUTIONS

I. INTRODUCTION

This study is an extension of recent work [1]* which attempted preliminary evaluation of the degree to which certain additives would reduce the shear-friction characteristics of high velocity water flow on a solid boundary. The earlier study, which involved fresh water solutions of the sodium salt of carboxymethycellulose (CMC), defined in a limited way the wall shear values for pipe type flows involving selected shear rates, temperatures, and additive concentrations.

The earlier study clearly demonstrated that under some flow conditions the additive could reduce wall shear values as much as 70 per cent. Furthermore, a simple power law shear relation served to characterize the fluid over a wide range of shear rates, and the test results were suitable for limited interpretation in the form of friction factor vs. Reynolds number. However, despite the confirmation of these significant benefits, the study was inconclusive in evaluating a number of important factors. These factors include the nature and range of flow transition, scaled extrapolations (diameter effects), degradation effects, influence of sea water, performance of more dilute solutions, and the relative merits of other additives.

The current investigation is intended to provide additional information relative to the problem areas disclosed by the earlier study.

II. DILUTE POLYMER SOLUTIONS - GENERAL CONSIDERATIONS

A. The Influence of Molecular Structure in Shear Flow

Pure water exposed to a laminar shearing action yields a linear relation between shearing stress and rate of shear. Increasing the rate of shear ultimately generates vorticity and a progressive transition to fully turbulent flow characterized by a shearing stress, which is approximated by a second power function of the rate of shear. Flow characteristics in the laminar regime are dominated by viscosity, an inherent molecular-scaled activity, while

---

*Numbers in brackets refer to the List of References on page 39.

those in the turbulent regime are dominated by some combination of molecular-scaled activity and a macro-scaled, mass-transfer, vorticity action.

If particles that are neutral in density or shape are added to the water either as molecular-size solutes or as macro-size dispersions or suspensions, only minor changes occur in the relations of shear stress to shear rate. However, as either the density or shape of the additive particles departs from neutral buoyancy or sphericity, the shearing characteristics of the mixture or solution depart from those of the solvent water. This departure is a function of the additive concentration and occurs in both the laminar and turbulent regimes of flow. The departure is evidenced as an increase in the shear stress values in the laminar regime and a decrease in the turbulent regime. For beneficial application to naval drag problems, favorable departures in the normally turbulent regime are sought.

The additive materials which currently appear most favorable in action do not involve appreciable change in density values, but rather depend on marked asymmetry of particle shape. The most effective turbulent drag reduction seems to be evidenced where the particle has a long rope-like configuration. Similarity of test results occurs with large fibrous particles of natural or synthetic origin or with molecular-size particles of either natural or synthetic origin. Since the limited evidence available indicates that suspensions involving large-size fiber units are difficult to maintain and handle in practice, drag reduction studies have largely dealt with dispersions or solutions involving additives of molecular size. (The term solution is generally used herein, although in most instances the mixture is believed to be a colloidal dispersion.)

Rope-like molecules which are soluble or dispersible in water occur in natural organic forms and many of those commonly available have been extracted quite directly from certain forms of sea weed, nuts, seeds, exudates, cellulose, etc. They may also be synthesized by controlled biological processes or formed from nearly iso-dimensional monomer molecules by building these into long-chain molecules by polymerizing. The resulting polymer molecular weights may run up to 1×10^6 in readily available products; materials of molecular weights up to 1×10^8 can be synthesized if necessary. The commercial methods of preparation of these high molecular weight materials usually involve somewhat random processes and yield an end product with molecules having a substantial range of weights. It is possible but not practical to fractionate this range to yield only materials of the highest weight. Many of these materials are intended as thickeners for foods and most are either digestible or physiologically inert.

Limited evidence indicates that shear reductions improve with increasing molecular weight of the additive, but a number of other molecular properties probably also exercise significant influence. Among these are the molecule linearity, stiffness. or coiling characteristics, hydration properties, molecular bond, concentration, etc.

It is important to note that, depending on the branching mode, a given molecular weight can be disposed in a molecule shape ranging from a single long linear string to a compact burr-like structure. The compact branching forms appear to contribute little turbulent shear reduction as contrasted to the linear forms. It is speculated that linear molecules, when exposed to shear in a fluid, align themselves with the general shearing structure and in this orientation inhibit lateral transfer mechanisms and thus depress the rate of energy dissipation in the fluid. This reduction in the rate of energy dissipation occurs in both the laminar and turbulent flow regimes. Water solutions which in laminar flow exhibit a shear thinning property (diminishing ratio of shear stress to shear rate) with increasing shear are known as pseudoplastic fluids. They are the principal subject of this investigation.

Clear evidence of the influence of the stiffness or coiling properties of the molecules on turbulent shear is lacking, but this factor is a variable in molecular structure and probably has a shear influence. It is speculated that disentanglement of coiled molecules contributes to high shear forces at low shear rates. It is further speculated that some polymer coils may possess substantial elastic properties which can absorb additional energy and develop peculiar normal forces in the disentanglement or aligning action of the flow. Fluids which exhibit these normal forces are known as viscoelastic. They do not conform to the flow characteristics of pseudoplastic fluids, and extrapolation of test results to other scales and boundary conditions is complex. Viscoelastic forces are believed to be relatively insignificant for the dilute solutions of concern here, but this is not certain.

Molecules also differ in their ability to solvate or hydrate in a process which attracts and holds water. Hydration can markedly increase the dimensions and mass of the molecule as an effective dynamic unit of the flow. It has been speculated that one possible explanation of pseudoplastic behavior of a polymer solution lies in the progressive shearing off of liquid carried by the additive as an envelope of solvation. The rate and extent of the hydration may be of importance in determining the manner and amount in which the dry additives can be used in naval applications. It is noteworthy that guar gum additives, which are among the most effective, are believed to solvate highly [2]. It is estimated that a hydrated linear polymer molecule of weight about 1×10^6 may have an effective diameter of about 1000 Angstroms (4×10^{-6} in.) and a length of 25,000 Angstroms (1×10^{-4} in.).

The ionization and other chemical characteristics of the polymer solution may vary widely depending on the processes employed in making the additive and on the nature of the solvent. Many high polymers are thus commercially available in a variety of types and require selection for compatibility with a particular solvent. For the studies under consideration it was particularly desirable that the shear characteristics of the solution remain favorable when sea water was used as the solvent. In addition to inherent differences in the polymer itself, many commercial forms also contain foreign materials which may or may not be soluble or otherwise influential in the use of the product. The active polymer constituents of many of the commercial forms may be as low as 30 per cent and as high as nearly 100 per cent by weight.

The relative tensile failure strength of the polymer chain is a function of the chemical constitution of the chain and is important to the end usefulness of the material as an additive. The long chains, which are apparently desirable for drag reduction purposes, are subject to greater tensile loadings than short chains when exposed to flow processes. In laminar shear processes, Merrill [3] found that the rate of change of shear rather than the absolute level of shear was the determining factor in evidence of failure or scission of long chains. However, in turbulent processes even gentle shaking of the fluid could cause scission of some types of long chains. Scission of the chain is manifested by a change in the shear flow characteristics of solutions which tend to degrade toward those of the pure solvent. Such degradation generally appears to be permanent. In some materials significant scission evidently does not occur in turbulent flow unless the latter is of considerable duration or high intensity. Among the more destructive dynamic actions are pumping, valve throttling, cavitation, high frequency oscillation, and high speed stirring as with a blender.

Studies of dynamic degradation [4] establish that the susceptibility to degradation generally increases with the increase in molecular weight. In view of the fact that all naval applications of dilute solutions would normally require dynamic fluid processes for purposes of mixing, hydrating, and distribution, it will probably prove impractical to effectively use polymers of extremely high molecular weight.

B. Graphical and Analytical Shear Characterizations

(1) The Newtonian Solvents

Pure water exposed to laminar shear flow exhibits a relation between shear rate and shear stress which is characterized by the Newtonian viscosity expression

$$\tau = \mu \, dv/dr \qquad (1)$$

In terms of the wall shear τ_o and laminar flow conditions for a cylindrical conduit, this expression assumes the form

$$\tau_o = D\Delta P/4L = \mu \, (8 \, V/D) \qquad (2)$$

Test evaluations of wall shear stress versus shear rate in a smooth tube of given diameter yields a straight line in logaritmic coordinates, as indicated by AB in Fig. 1. For this case the flow is laminar and of constant temperature. The slope of this line is unity and the ordinate intercept at $8 \, V/D = 1$ yields the value of μ.

Similar laminar flow tests at the same temperature in a tube of smaller diameter yield a similar form of plot, but at a different position on the $8 \, V/D$ scale. Such a plot is represented by the line A'B' in Fig. 1. For all practical values of shear rate and for all tube sizes which may be tested, laminar flow conditions will yield data that would fall on a common straight line. Such a line of unity slope is characteristic for all Newtonian fluids, including water, and for a given fluid yields a constant value for the viscosity μ.

A repeat of such tests at a somewhat elevated temperature again yields a straight line of unity slope, but with lesser values of τ_o and μ. A repeat at lower temperatures in turn yields greater values of τ_o and μ.

If, in a given tube test of this type, the shear rate is further progressively increased, the flow will eventually depart from a laminar character in a distinctly transitional change, as shown at C or C' in Fig. 1. The Reynolds number of the flow corresponding to the point C will normally be about 2000. It is not generally appreciated that the departure from laminar regime occurs very gradually at values considerably lower than $N_{Re} \approx 2000$, so that the region BC is actually a near-laminar or pseudo-laminar region. In the earlier tests of this program [1], the departure was generally observable at about $N_{Re} = 1500$. Other investigations have generally found a small but definite deviation from laminar flow at values of N_{Re} exceeding 1000. In view of this, all experiments designed to evaluate μ must be confined to tests in the linear portion of the unity slope line of Fig. 1 (i.e. portion AB or A'B').

A further increase in shear rate above the values represented by point C yields rapidly increasing values of τ_o shown as the curve CD. At still higher shear rates, the flow curve assumes the shape of the straight line DE. It is to be noted that in the regions AB, BC, and DE, conventional manometric measurements of ΔP yield essentially steady and reproducible values. In the region CD, in contrast the ΔP-values will usually evidence a widely ranging unstable variation. In Newtonian flows the region DE is considered to be fully turbulent and the region CD is considered transitional between laminar and turbulent. The region CD normally extends over only a very limited range of values of $8\ V/D$. A complete flow test in a tube of diameter smaller than that which yielded the data ABCDE will yield a curve such as A'B'C'D'E' as shown in Fig. 1.

A wide variety of tube or pipe test data, similar to that of Fig. 1, has been obtained by many experimenters and subjected to study by many analysts to determine universal correlating parameters. Among the more generally useful and accepted forms of correlation is one which relates the dimensionless Fanning friction factor f with the Reynolds number flow parameter N_{Re} in a graphical form typified by Fig. 2. The correlation equation for the laminar portion of this plot is

$$f = 16/N_{Re} \tag{3}$$

A widely accepted and simple correlating equation for the turbulent range where $N_{Re} < 100{,}000$ is given by the equation of Blasius:

$$f = 0.079/N_{Re}^{1/4} \tag{4}$$

For values including $N_{Re} > 100{,}000$ a better fit with the data is achieved with the more complex Karman-Prandtl resistance equation for turbulent flow in a smooth pipe:

$$1/\sqrt{f} = 4\log N_{Re}\sqrt{f} - 0.4 \tag{5}$$

It is to be noted that the constants of Eqs. (3), (4), and (5) result from the use of Fanning's f which is one fourth the value of Darcy's f. Fanning's f is used herein because of its general acceptance in the field of chemical engineering which provides the greatest source of non-Newtonian flow data and analysis.

In the material that follows, it will be shown that the polymer water solutions, which exhibit remarkable drag reducing properties, are fluids yielding data that are inconsistent with Eqs. (1) and (2) for the Newtonian fluid. These fluids are known as non-Newtonian and do not directly conform to Eqs. (1) and (2) and to their expansions in Eqs. (3), (4), and (5). However, because of the much greater prior art relating to Newtonian fluids, the present treatment of non-Newtonian fluids leans heavily on modifications of the analytical procedures which have proven workable in dealing with Newtonian fluids. Some of these modifications are discussed in the pages that follow.

(2) Non-Newtonian Aqueous Solutions

When dilute water solutions of high molecular weight polymers are subjected to laminar shearing flow in a cylindrical conduit, they fail to yield the type of AB-line which characterizes the Newtonian flow in Fig. 1. Instead, laminar tests of these solutions in tubes of various sizes over a wide range of 8 V/D define a curve such as A"B"X". A curve of this type is defined as representing a shear thinning or pseudoplastic non-Newtonian fluid. This fluid is considered to be non-Newtonian because the curve is not fitted by either of Eqs. (1) and (2) which serve to define a Newtonian fluid.

If the laminar tests could be carried out over a very wide range of values of 8 V/D, the extreme left end of the curve would swing parallel to the straight line representing the Newtonian fluid (water) which serves as the solvent. Similarly, the right end of the curve would normally swing parallel and quite close to the Newtonian line of the solvent fluid. In some intermediate central region, the curve would normally contain a straight length between the inflection points of this S-type curve. The segment A"B" of Fig. 1 is part of such a line. Fortunately, many dilute polymers yield laminar shear data for which the central portion remains a straight line throughout the entire range of 8 V/D which may be of interest. In consequence of this rather commonly exhibited linearity in the central region, an empirical functional relation known as the power law is frequently adopted for characterizing these fluids in this region. For the more general case of two-dimensional shearing conditions, this expression takes the form:

$$\tau = K(-dv/dr)^n \tag{6}$$

For flow conditions in a tube and considering the shear condition which exists at the wall, it has been established [5] that

$$\left(-\frac{dv}{dr}\right)_w = \frac{(3n' + 1)}{4n'} \frac{8V}{D} \tag{7}$$

where

$$n' = \frac{d[\log (D\Delta P/4L)]}{d[\log (8\ V/D)]} \tag{8}$$

and

$$\tau_w = D\Delta P/4L = K' (8\ V/D)^{n'} \tag{9}$$

Equation (8), as related to Fig. 1, gives the slope n' of the line segment A"B", and the intercept of this line with the ordinate at log (8 V/D) = 1 is the K' value.

As in the case of laminar Newtonian flow characterized by Eq. (2), the magnitude K of Eq. (6) and the magnitude K' of Eq. (9) are closely related to μ, and K' is a measure of consistency which is known as the consistency index. The magnitude n' is that property of the fluid which indicates the degree of non-Newtonian behavior referenced from the Newtonian condition $n' = 1$. For the shear thinning type of fluids represented by the test polymer solutions, $n' < 1$.

Although Eqs. (6) and (9) are similar, the latter is more convenient for use in this study because the necessary tests were conducted in more suitable conduit type flow facilities.

For the purposes of this study, Eq. (9) will be used for all fluid characterizations. It should be noted however, that the values of K' and n' can be utilized to evaluate Eq. (6) by suitable substitutions. The substitution in the case of n' may be derived from a plot such as Fig. 1 [or from Eqs. (6), (7), and (8)] for which

$$\frac{1}{n} = \frac{1}{n'} + \frac{d\left[\log\left(\frac{3n' + 1}{4n'}\right)\right]}{d[\log \tau_w]} \qquad (10)$$

If n' in Fig. 1 does not change in the region of interest (a straight segment as A"B"), the equation yields $n = n'$. In the event that n' is not constant, n' must be evaluated in terms of the local slope or tangent to the curve. The substitution in the case of the consistency index is derived from the expression

$$K' = K\,[(3n + 1)/4n]^n \qquad (11)$$

The preceding concludes coverage of the relations applying to the laminar non-Newtonian case.

If the laminar flow test conditions in a given tube yield a linear segment such as A"B" in Fig. 1, a further increase in flow rate must ultimately produce a transitional departure from the pure laminar condition. This departure is depicted as commencing at point B" in Fig. 1 and extending to point C" before starting the rapid transition change C"D" which introduces the fully turbulent flow region D"E".

Similar non-laminar flow tests in a smooth tube of smaller diameter result in a shift in position of the curve, with B"C"D"E" departing further to the right. For a larger tube, the B"C"D"E" curve will occur further to the left.

As with the Newtonian fluids treated previously, data of the type just discussed may be analyzed to determine general frictional correlation parameters. For the laminar flow data, Metzner and Reed [5] established this by preserving the form of the standard Newtonian relation $f = 16/N_{Re}$. This correlation was achieved by a new form of Reynolds number which is given by either of the following equivalent expressions:

$$N'_{Re} = \frac{D^{n'} V^{2-n'} \rho}{K' 8^{n'-1}} \tag{12}$$

or

$$N'_{Re} = \frac{DV \rho}{K' (8 V/D)^{n'-1}} \tag{13}$$

These general equations also relate to Newtonian fluids which are the special case where $n' = 1$. For this condition N'_{Re} reduces to the conventional Reynolds number.

Experience has proven that pipe friction data involving a very wide variety of shear thinning or pseudoplastic non-Newtonian fluids tend to conform in the laminar region to the modification.

$$f = 16/N'_{Re} \tag{14}$$

However, when these plots of f vs. N'_{Re} are extended into the turbulent region, with N'_{Re} determined from Eq. (12) or (13), the data fail to conform to either the Blasius Eq. (4) or the Karman-Prandtl Eq. (5). Although many analysts have attempted to use a simplified flow model to obtain a general correlation of existing turbulent data, success has been attained only for rather limited systems.

Of all the existing methods, that of Dodge and Metzner [6] is probably most widely applicable. As shown in Fig. 3, this consists of a plot of f vs. N'_{Re} with a separation into a family of curves of different n'-values. The data involved tests of a variety of polymer solutions and solid-liquid suspensions with n' varying from about 0.36 to 0.73. It is noteworthy in Fig. 3 that, although the f-values for the non-Newtonian flows with $n' < 1$ are much lower than for the Newtonian case of $n' = 1$, the transition from laminar to turbulent flow occurs over a relatively small range of N'_{Re}.

Tests with solutions of carboxymethylcellulose (CMC) [1, 7] show a rough similarity to the general pattern of the n' family of curves of Fig. 3 but, as shown in Fig. 4, the values of f are significantly lower for the CMC solutions. More important perhaps is the fact that much of the friction reduction is derived from the greatly increased range of N'_{Re} over which departure from laminar and transition occur. The CMC fluid is also peculiar in that, unlike the fluids in Fig. 3, the data of Fig. 4 are valid for only one pipe diameter. Tests [6] have demonstrated that a change in the diameter of the test rheometer produces a significant shift in the family of curves.

It is noteworthy that the extended transition conditions evidenced with the CMC solutions have been noted by Metzner and Reed [5] also in tests involving high concentration of suspended minerals, as shown in Fig. 5. Unlike the fluids of Figs. 3 and 4, the latter fluids do not appear to terminate in an n' family of curves in the turbulent region, but tend with increasing N'_{Re} to return to the friction curve for water.

Since the literature relating to tests of the very dilute polymer solutions of interest in this program is very limited, this study has extended the test range and sought to evaluate comparative conformance with the known performance patterns of Figs. 3, 4, and 5.

III. THE CAPILLARY TUBE RHEOMETER STUDIES

A. Equipment and Procedure

A variety of devices has been evolved for determination of the rheological properties of non-Newtonian fluids. In general these involve either some form of a rotational shearing boundary or a capillary tube viscometer. While data from either form can be reduced to fundamental relations and flow diagrams with complete agreement of results, each has certain advantages and disadvantages. In the current tests the capillary tube type has been selected for all fluid characterizations. The selection was based primarily on the feasibility to establish fluid properties with minimum shear degradation because of the very brief exposure of the fluid sample in a one-pass type of test. Since the program was to include a pipe type apparatus for boundary layer studies, data from the capillary tube also permitted direct similarity extensions.

In order to achieve both laminar and turbulent flow data over a wide range of shear rates the tests were conducted with three different capillary tube diameters. These nominal diameters were 0.013, 0.054, and 0.104 inch.

The tube length was 1000 diameters in all cases. This arbitrary selection of length was based on the recognition that fluid characterization errors contributed by entrance, exit, temperature, etc., diminished with increasing length while errors contributed by shear degradation might increase with length. The straight tubes were of standard stainless steel and were presumed to have a "hydraulically smooth" surface, as was subsequently verified.

In the test apparatus the square-ended tube drew from a relatively large reservoir (about 1000 cc.) and discharged horizontally to the atmosphere. Both the reservoir and tube were provided with insulated water jackets through which temperature controlled water was continuously recirculated.

The temperature of the test fluid was taken as the temperature of the recirculating coolant just prior to a test run. The coolant temperature could be determined to within about 1/4° F. It was recognized that an isothermal condition could not be maintained within the test fluid at high shear rates and that the temperatures as read might be as much as 2° less than the mean temperature which actually prevailed. It is conceivable that local temperatures may have experienced a wide range of values.

Discharge through the tube was initiated by a driving pressure head applied to the dome of the liquid reservoir. This head ranged from about 2500 ft to 3 in. of water. The higher pressures were obtained by use of bottled nitrogen and the lower pressures were supplied by the Laboratory compressed air system. Pressures were read from meters connected to the reservoir dome. The high pressures were read from calibrated quality Bourdon gages and the low pressures were read from manometers. The effective friction head at high pressures was derived from the Bourdon gage reading with adjustment for entrance effects. In tests at low pressures the applied pressure was adjusted for entrance effects plus the gravitational head on the system, including variations in the latter.

The mean flow velocity for the capillary tube tests was evaluated from time-weight measurements of the free discharge from the tube. Both the test time and collected weight were made sufficiently great so that the discharge in most cases could be evaluated with an error no greater than about one per cent.

All solutions tested in the capillary studies were prepared with the selected additive and either distilled water or sea water as the solvent. Mixtures were proportioned by careful weighing of the constituents, including compensation for the hygroscopic moisture in the additive.

Since the additives were organic materials which could be subject to bacterial spoiling, solutions were batched in quantities that could be tested within a day after preparation and a suitable preservative was added to them. Such batches were in general about 3 gallons in volume.

Earlier tests had shown that solutions of long chain polymers were subject to shearing scission which had marked effects on their subsequent friction reduction characteristics. Hence, in order to obtain optimum drag reduction values in these tests, it was important to minimize all shearing actions in preparation of the solutions. To accomplish this, the dry additives (powdered or granulated) were added to the water as the flowing water was admitted to the mixing vessel. The addition and dispersion were accomplished by shaking the dry material onto the surface of a thin water vortex. The vortex was formed by admitting the water tangentially at the edge of a bowl having a center discharge opening into the storage vessel. The bowl employed was the metal top of a silex-type coffee maker. With most additives, dispersion was accomplished fairly effectively with this one-pass flow system. Some additives showed a tendency to agglomerate in the dispersion process. Subsequent occasional gentle manual stirring was employed to bring the dispersions into full solution. The solutions were considered fully hydrated and ready for testing after they had been visually clear for not less than two hours.

The test solution was approximately tempered to the selected temperature before admission to the rheometer reservoir and was held in the reservoir sufficiently long to assure full temperature adjustment. The discharge cycle of the rheometer was controlled by a quick-acting plug valve applied to the downstream end of the capillary tube. Discharge measurements were commenced after first normalizing the flow in the capillary.

With the exception of limited degradation studies, which are to be discussed later, all samples were run through the rheometer only once and then discarded.

B. Data Handling and Corrections

The value of the wall shear τ_w was obtained by evaluating its equivalent $D\Delta P/4L$ from the measured data. The value of ΔP was as read either on the Bourdon gage or manometer and subsequently adjusted for entrance effects and gravitational head.

The pressure adjustments for the entrance effects were considered to consist of two parts. The first part concerns the portion of the reservoir pressure head which is effectively converted to kinetic energy in eventually achieving a fully developed velocity profile in the capillary. The second part concerns the portion of the reservoir pressure which is consumed in overcoming excess friction in the process of achieving the fully developed profile.

In the case of laminar flow of a Newtonian fluid, the mean kinetic energy of a flow having a fully developed parabolic velocity distribution is twice the average velocity head. For a non-Newtonian dilute pseudoplastic fluid, Metzner [8] shows that the velocity profile tends to flatten somewhat and accordingly the mean kinetic energy will be something less than twice the average velocity head. On the other hand, the mean excess friction has been shown by Bogue [9] to be about one quarter of the average velocity head for a Newtonian fluid, with a presumed increase above this value as the fluid becomes more non-Newtonian. Since avaliable information does not further clarify the value of this adjustment for a non-Newtonian fluid with $n' \approx 1$ and since a degradable fluid cannot be used to accurately evaluate end effects in a given tube system, the entrance deduction for laminar flows has been arbitrarily taken in this case as two times the average velocity head.

The above rationalization has been applied also to non-laminar flows, but recognizing that the kinetic energy of the fully developed velocity profile is more nearly equal to one velocity head than to two. Since available data for turbulent non-Newtonian flows are extremely limited, the entrance deduction adjustment for the turbulent data of this study has been arbitrarily taken as one average velocity head.

Because the diameter of the capillary tube has a strong influence in the fluid characterization, it was important to determine it with good accuracy. In this case the tube diameters were established by running calibration tests using distilled water, a fluid known to have universally stable viscosity characteristics. These tests were run at 70° F. under conservative laminar conditions ($N_{Re} < 1500$) and the test data were adjusted to fit a logarithmic plot of $D\Delta P/4L = K' (8\ V/D)^{n'}$. In the case of distilled water, the standard viscosity value of $K' = 2.05 \times 10^{-5}$ and $n' = 1.00$ were used for diameter adjustment. The adjusted diameter values for the three test rheometers were determined by this procedure to be 0.0136, 0.0540, and 0.1053 inch.

The validity of the above methods of adjusting entrance effects and diameter values is believed to be quite good in view of the fit which the resulting water data make in both the laminar and turbulent regions of the subsequent plots of f vs. N_{Re}.

The values of Fanning's f were obtained from the pressure drop data by use of the relation

$$f = \frac{D\Delta P}{4L} \Bigg/ \rho \frac{V^2}{2} \tag{15}$$

and the values of n' and K' were obtained respectively, from the slope and intercept of the laminar portion of the logarithmic plots of $D\Delta P/4L$ vs. $8\ V/D$, in accord with Eq. (9).

C. The Solvent Fluids

Fundamental calibrations of the capillary rheometer tubes and limited initial tests of polymer solutions employed distilled water as the solvent. This solvent was used because of its ready availability, known and stable viscosity characteristics [10], and its reproducible action with various additives. However, since naval application of drag reduction additives would normally involve sea water and because of possible reactions between the additive and sea water, it was considered essential to conduct most of the additive evaluations with sea water.

The required sea water was obtained through the assistance of the Office of Naval Research which enlisted the generous support of Mr. M. W. Johnson of the Hudson Laboratories of Columbia University. The water was collected in September 1963 in Long Island Sound about ten miles offshore from Bridgeport, Connecticut, with the tide coming in from the east. The water was collected in lined 55 gallon steel drums. One ounce of powdered Dowicide G (Dow Chemical Company, Midland, Michigan) was added to each drum at the time of collection, to inhibit biological activity during storage. This water remained free of any visual or odor evidences of change for the eight month period in which it was used following its collection. It is to be noted that while Dowicide G is a biocide recommended by many polymer manufacturers for inhibiting biological activity in their materials, its presence in the sea water may have had a detrimental influence on some of the evaluations recorded in Table I (page 19).

No direct determination of the salinity or other chemical properties of this solvent were made, but viscosity evaluations were run in the capillary tube rheometer. These evaluations employed a logarithmic plot of the data in the form of $D\Delta P/4L$ vs. $8\ V/D$, and a good data fit was achieved with a line of unity slope ($n = n' = 1$) to yield $K = K'$ values of 3.425×10^{-5} at 40° F., 2.210×10^{-5} at 70° F., and 1.842×10^{-5} at 85° F. It should be noted that the salinity of sea water is normally about 3.5 per cent by weight and that the accepted values of viscosity for this concentration [10] are in good agreement with the above measured values.

D. Preliminary Screening Studies of Various Additives

The additive polymers employed in the evaluations were those which various sources of information indicated might yield significant drag reduction evidences. A large number of materials were recommended but, because of the time-consuming nature of capillary tube testing, the initially selected materials were subjected to preliminary screening to isolate a single material for use in more intensive tests.

This preliminary screening consisted of capillary tube determinations of the values of $D\Delta P/4L$ for $8\ V/D$ values ranging from about 3×10^2 to 3×10^5 inverse seconds, which included a range of conditions well above the laminar. These tests were conducted in the capillary tube of 0.054-in. diameter at a temperature of 70° F. with sea water solutions of 0.1 per cent additive by dry weight. In retrospect, it appears that a somewhat lower concentration may have been a more useful basis of comparison.

From preliminary plots of the data of these various tests, it was decided that the material Polyhall-27 provided the greatest shear reduction benefits within the test range of $8\ V/D$. As determined from these tests the significant characteristics of this material were as follows:

1. In the laminar region, the curve was only slightly different from that of water. The values of n' and K' were close to those of water, so that friction for laminar flow conditions would accordingly be low.
2. Compared to a curve for water there was no evidence of an abrupt low shear rate transition to turbulence.
3. The curve for higher shear rates showed a general parallelism to that for water, but with markedly lower values of shear stress.

The other 15 materials which were subjected to the preliminary screening generally differed from Polyhall-27 in that the laminar flow was more viscous and non-laminar shear benefits were less. The more viscous character for laminar flow is indicated by the higher values of K'. This was also generally accompanied by lower values of n'.

Information relative to these materials is summarized in Table I. It is to be noted from this summary that many of the materials yielded performances quite similar to that of Polyhall-27, and it is acknowledged that under somewhat different screening conditions a different order of selection may well have resulted. It is also important to note that the amount of active polymer material in the various samples may have differed considerably (Polyox is believed to be nearly 100 per cent active). Performance comparisons on the basis of equal dry weights may therefore be somewhat misleading as to optimum values that might be obtained.

Caution should be exercised in comparing the n' and K' data of Table I with the results of other investigations. For example, the K' value for CMC in the table is considerably greater than the values obtained in Ref. [1] for the same material. The nature of this difference is, however, accountable when it is recognized that the earlier tests involved mixing and handling procedures which probably introduced significantly greater mechanical degradation effects than the current tests.

E. Wide Range Studies of the Additive Polyhall-27 in Sea Water and Comparisons with Polyox-301 and Westco-J2

(1) Range of Tests

In order to provide a better perspective as to the frictional performance of dilute sea water solutions of a typical good polymer Polyhall-27 was tested under conditions which were deemed applicable to the field problem and yet workable in a limited laboratory program. To achieve this perspective, it was considered desirable to obtain data of $D\Delta P/4L$ and $8\,V/D$ and to calculate values of f and N'_{Re} for the broadest workable range of shear rates in tube type studies.

To clarify the possible influence of tube diameter effects, it was considered desirable to employ at least 3 tube sizes within a workable range. The selected tubes had nominal diameters of 0.013, 0.054, and 0.105 in., as previously described.

To clarify the possible influence of temperature in prototype applications, it was considered desirable to conduct tests in the range from 30° to 85° F. Since low range temperatures were difficult to obtain and control, a compromise lower limit of 40° F. was finally employed for practical reasons.

Table 1 - Some Characteristics of the Various High Molecular Weight Polymer Additives and Their Aqueous Solutions

Trade Name	Chemical Identification	Manufacturer	Molecular Weight	Solvent Used	pH*	n'*	K'*
ADM - 7097	Polysaccharide gum (fermentation)	Archer Daniels Midland Co., Minneapolis, Minn.	24×10^6	Distilled water	6	-	-
B - 1459		Commercial Solvents Corp., New York, N. Y.	-		6	-	-
B - 1459		Elanco Products Co., Indianapolis, Ind.	-		6	-	-
Carbopol - 934	Carboxyl vinyl polymer	B. F. Goodrich Chemical Co., Cleveland, Ohio	-		8	0.73	0.0025
CMC - 7HSCP	Sodium carboxymethylcellulose	Hercules Powder Co., Wilmington, Del.	$(5 \text{ to } 50) \times 10^4$		6	0.62	0.0026
				Sea water	6	-	-
Dextran	Alpha glucosyl polysaccharide	Pharmacia, Uppsala, Sweden	$(5 \text{ to } 40) \times 10^6$	Distilled water	4	0.975	0.000030
ET - 597	Sulfonated polyvinyl toluene	Dow Chemical Co., Midland, Mich.	~~8×10^6~~	Sea water	7-8	-	-
ET - 720	Sodium polystyrene sulfonate		$(8 \text{ to } 9) \times 10^6$		6	0.98	0.000036
Jaguar - 124	Modified guar gum	Stein, Hall, and Co., New York, N. Y.	-		6	-	-
Kelco Gel HV	Sodium alginate	Kelco Co., San Diego, Calif.	-	Distilled water	6	-	-
Kelgin HV			-		6	-	-
Kelzan	Xanthan gum		-		6	0.59	0.00182
Kelzan H			-		6	0.58	0.00126
Methocel - 90HG	Methyl cellulose	Dow Chemical Co., Midland, Mich.	-		5-6	-	-
Polyhall - 27	Non-ionic polyacrylamide	Stein, Hall, and Co., New York, N. Y.	-	Sea water	6	0.975	0.0000369
Polyox - 301	Ethylene oxid polymer	Union Carbide Chemicals Co., New York, N. Y.	$\text{to } 5 \times 10^6$		6	-	-
				Distilled water	6	0.88	0.00015
Reten - 205 MX	Catonic polymer	Hercules Powder Co., Wilmington, Del.	-	Sea water	6	0.945	0.000050
Separan - NP20	Non-ionic polyacrylamide	Dow Chemical Co., Midland, Mich.	2×10^6	Distilled water	5	0.735	0.00067
					6	0.90	0.000115
Westco - J2	-	The Western Co., Dallas, Texas	2.2×10^5	Sea water	6	0.85	0.000193

*The test data were obtained for concentrations of 1000 ppm at 70 F. in a 0.054-inch rheometer tube 1000 diameters long. The rheological magnitudes n' and K' were not determined in some cases either because the data were limited to the post-laminar range for purposes of drag benefit comparison or because it was found unfeasible to obtain a strictly laminar regime.

The upper limit of 85° F. was readily obtained. An intermediate value 70° F. was arbitrarily selected because of the relative ease with which it could be employed.

To contribute insight into the influence of additive concentration, the studies were conducted with concentration values of 0.001, 0.01 and 0.1 per cent of additive by dry weight. These values correspond respectively to values of 10, 100, and 1000 parts per million of additive.

Since the shear rate values to be employed in prototype applications were not well defined, the program sought the highest practically attainable values with coverage extending from these downward into the laminar range. While operation in the purely laminar range is probably of minor importance in any eventual applications, the limiting values are important for analytical purposes and laminar values are essential for characterizing the fluid for use with Eqs. (6) or (9). The pressure system described previously was designed to provide the selected shear rate range for the contemplated test conditions.

Although the preliminary screening of additives lead to a test program centering around Polyhall-27 other Navy-sponsored studies [13, 14] have had occasion to use the additives Polyox-301 and Westco-J2. In light of this, it was considered desirable to provide limited comparative cross ties between the current work and these other studies. This was accomplished by subjecting these other additives to the same type of characterization as Polyhall but with a smaller range of conditions.

(2) The Evaluations of n' and K'

The values of n' and K' pertinent to the selected shear rates were derived from data obtained from capillary rheometer tests conducted in accord with the descriptions under Sections II (A) and II (B). The test data useful for this evaluation were limited to those which corresponded to the definitely laminar region and which plotted with good linearity in logarithmic graphs of $D\Delta P/4L$ vs. $8\ V/D$. For a given tube size this corresponds to the region A"B" of Fig. 1. Such data for a given polymer concentration and temperature in several tube sizes, yielded curve segments similar to those of

A"B"X" in Fig. 1. In the general case and for very wide ranges of shear rate, A"B"X" may be expected to be a curve. However, a great many shear thinning fluids have in the past shown excellent linearity for a wide practical range. Fortunately, this proved to be the case for Polyhall-27 in the range of 8 V/D from 4×10^2 to 1×10^5 sec^{-1} which the tests covered. For this range of conditions any particular selection of temperature and concentration data for laminar conditions fitted one common line for all 3 tube diameters and yielded the values of n' and K' shown in Fig. 6.

(3) <u>Shear Performance Characterizations</u>

The results of the rheometer tests with the three relatively dilute solutions of Polyhall-27 are presented, among others, in Figs. 7 and 8. Figure 7 is a logarithmic flow diagram plot of DΔP/4L vs. 8 V/D, covering the data for the test runs of all three concentrations, but only in the 0.054-in. tube at 70° F. as these data are representative also of those for the other tube sizes and temperatures. Figure 8 on the other hand, is a logarithmic plot of the Fanning friction factor f vs. a modified Reynolds number N'_{Re}, covering all concentrations, tube sizes, and temperatures used in the rheometer tests. All three Polyhall curves in Fig. 7 exhibit the following characteristic features:

(1) A similarity to the sea water solvent within the strictly laminar regime, which is fairly independent of the concentration.

(2) An early departure from this regime into a near-laminar or pseudo-laminar regime, the departure occurring earlier with increasing concentration.

(3) A pattern of delayed transition extending through the entire test range of 8 V/D beyond the pseudo-laminar, with a tendency towards eventual approach to the definitely turbulent regime, the beginning of the approach evidently occurring at higher values of 8 V/D as concentration increases.

(4) A substantial benefit in wall shear stress relative to that of the solvent, commencing generally within the transition region of the solvent and, of course, extending throughout the entire transition range of the additive solution. The benefit occurs sooner for the lower concentration and is higher within the region up to the point where the corresponding curve intersects the curve for the next higher concentration. Accordingly, maximum benefit occurs with the highest concentration,

> but only at the highest value of 8 V/D.
>
> It should be noted that the range of this test series using capillary tubes was insufficient to furnish evidence as to the pattern and magnitude of the benefit within the definitely turbulent range; such evidence was obtained in subsequent tests in the pipe-size system.

For purposes of comparison, Fig. 7 presents also results of similar rheometer tests on two concentrations each of Polyox-301 and Westco-J2. It is seen that the corresponding Polyhall-27 solutions are more beneficial throughout most of the test range.

The characteristics enumerated above are evidenced also in the presentation of Fig. 8, although in a modified form because of the comparatively arbitrary nature of the Reynolds number parameter used in the latter plot.

(4) Friction Factor Evaluations

Evaluation of Fanning's friction factor f for the rheometer test series described in Section E3 above, was made from capillary tube pressure drop data in accord with the procedures described in Section II (B). These values were then plotted on a log-log scale against a corresponding Reynolds number of the form of Eq. (12). The Reynolds number was calculated from the tube flow data together with the appropriate values of n' and K' from Fig. 6. The resulting graph is shown in Fig. 8.

For purposes of comparison, data relating to Polyox-301 have also been added to Fig. 8.

In examining Fig. 8 it should be noted first that, although a plot of the laminar flow data for $N'_{Re} < 1000$ yielded a good fit with the curve $f = 16/N'_{Re}$ (Eq. 14) in a manner similar to Figs. 2 and 4, this portion of the total plot is omitted in Fig. 8 so as to permit graphical amplification of the more important data for $N'_{Re} > 1000$.

The friction data of Fig. 8 are significant in that they establish that very dilute water solutions of additives such as Polyhall or Polyox are capable of sustaining a low friction, pseudo-laminar flow to unusually high Reynolds numbers. The occurrence of this pseudo-laminar regime has been approximately defined in Fig. 8 by the empirically fitted line $f = 1.5/(N'_{Re})^{2/3}$. Data points below this line represent a pseudo-laminar flow comparable to B"C" in Fig. 1, while those above the line represent transition conditions comparable to C"D" in Fig. 1.

The line $f = 1.5/(N'_{Re})^{2/3}$ was arbitrarily drawn to meet the curve of Eq. (14), $f = 16/N'_{Re}$, at the intersection which the latter curve makes with that of Eq. (4), $f = 0.079/(N'_{Re})^{1/4}$. The fact that this common intersection occurs at a Reynolds number of 1200, which is the approximate upper limit for true laminar flow, is perhaps significant.

The data of Fig. 8 are also significant in that transition departures from a pseudo-laminar flow condition do not occur at a common Reynolds number (≈ 2100) as is the case with Newtonian fluids. Neither do they occur in a narrow range of N'_{Re} as for the non-Newtonian fluid CMC in Fig. 4, nor as an orderly function of n' as was shown in Fig. 3 for various non-Newtonians. Rather, it appears that transition is some more complex function of N'_{Re}, additive concentration, and tube size.

It also appears from Fig. 8 that the line $f = 1.5/(N'_{Re})^{2/3}$ is in general a fair fit for the more concentrated solutions, but is a very conservative measure of f for the weaker solutions at low Reynolds numbers.

Of the two additives used in these tests, Polyhall-27 provided a somewhat lower f value than Polyox-301 in most of the pseudo-laminar flow range, but Polyox-301 persisted in the pseudo-laminar regime to significantly greater N'_{Re} values.

Temperature does not seem to significantly influence the magnitude of the frictional resistance in the pseudo-laminar flow regime, but transition departure from this regime appears to be further delayed with an increase in temperature.

As in the case of the plot of Fig. 7, the representation of Fig. 8 demonstrates the pattern of approach to the turbulent regime of the solvent, occurring at different values of N'_{Re} depending on the additive and test conditions, but does not cover the turbulent regime proper.

(5) Shear Degradation Tests

As indicated earlier, it was anticipated that the long chain molecules of the test additives would be inherently subject to scission degradation when exposed to severe shear conditions. Accordingly, the principal additive evaluations were conducted using mixing procedures and one-pass flows designed to minimize this degradation. However, in addition to this one-pass information, it was considered desirable to conduct additional limited tests to determine, at least roughly, the sensitivity of the material to continued shear exposure. For this purpose, the test fluid was subjected to two different procedures. In the first, the previously described capillary rheometer was used but a test fluid sample was repeatedly passed through the blow-down process. In the second system, a given fluid sample was sheared by a rotary mechanical mixer.

The results of the first type of degradation test on the selected test fluid Polyhall-27 are shown in Fig. 9 as a logarithmic plot of $D\Delta P/4L$ vs. 8 V/D. For this test, fresh solutions of Polyhall-27 in sea water, in concentrations of 0.10 and 0.01 per cent were passed through the tube of 0.054-in. diameter and 1000 diameters length at a temperature of 70° F. The blow-down pressures employed covered only the more meaningful high shear range, and the successive tests were run, first with progressively increasing and then progressively decreasing shearing action. For comparative purposes, the flow curve for sea water and the normal one-pass shear data for the same fluids are also included (larger range tests of Polyhall-27 and sea water are shown in Fig. 7).

For comparative purposes, the material Polyox-301 was similarly subjected to repeated capillary tube flow tests. In these tests, summarized in Fig. 10, concentrations of 0.10 and 0.01 per cent additive in sea water were likewise used in the 0.054-in. tube at 70° F. The tests were conducted in the same general way as those on the Polyhall summarized in Fig. 9.

Figure 10 shows that Polyox-301 at 0.01 per cent concentration degrades in much the same manner as Polyhall-27 at the same concentration, but the total degradation is much lower for the Polyox.

The shear data for the 0.10 per cent solutions of both additives are markedly different from those for the 0.01 concentrations, in that shearing action seemingly improves the frictional performance of the material. While this appears to be irrational, analysis of the wide range one-pass shear data, summarized in Fig. 7, shows that many of the solutions have shear regions in which the friction performance improves with increasing dilution. Shear degradation in these limited regions should then demonstrate improved performance as the fluid degrades from a higher concentration to the equivalent of a lower concentration. This is illustrated in both Figs. 9 and 10.

It should be noted that mechanical degradation in the repeated-pass tests was probably due not only to the shearing action in the tube flow but also to the splashing jet action in the discharge collection vessel. Impinging free liquid surfaces impose pressure waves of steep gradient and may well approximate the damaging conditions of sonic degradation [4, 11]. The intensity of this splashing degradation has been observed by others [12].

The mechanical mixer shear-degradation studies employed a standard Waring Blender (Catalog No. 700A). This device rotates a small blade at about 15,000 rpm in a limited sample of material, thus providing a fairly intense shearing action. For these tests the sample was 575 milliliters. Although the original temperature of the sample was always 70° F. long mixing exposures increased the temperatures to as much as 140° F.

A given sample of solution was placed in the device and mixed for a preselected time. Following mixing, the sample was placed in the capillary rheometer (0.054-in. dia, 1000-dia length), normalized to 70° F., and discharged at a selected pressure condition. These capillary tube characterizations were then plotted to show the influence of length of exposure of the sample to the mixer action.

The mixer degradation tests for Polyhall-27 concentrations of 0.10 and 0.01 per cent are shown in Fig. 11, while those for a Polyox-301 concentration of 0.10 per cent are shown in Fig. 12. These plots demonstrate that a dilute solution will degrade to a water-like character more quickly than a more concentrated solution, and that Polyox appears to degrade somewhat slower than Polyhall. The initial reverse degradation of Polyox is again evident in Fig. 12 as it was in Fig. 10.

In later discussions relative to tests in a recirculating pipe system, consideration is also given to observations of degradation due to cavitation.

F. Fish Slime Studies

Most general references regarding the physiology of fish include a statement to the effect that the mucous coating or slime on the exterior of a fish is intended at least in part to reduce body friction in the water. No validations of such statements appear in the literature on fish but independent evaluation attempts have been made by investigators concerned with body drag. These evaluations include early towing tank drag tests of anesthetized pike with and without a slime coating [15], and other tests [16] of a gravity propelled streamlined body which was dropped with and without a fish slime coating. Both of these programs failed to show any really significant effects from the slime coating, although they rationalized a possible association between the presence of fish slime and the extent of a laminar boundary layer with real fish.

While the foregoing tests lend no support to the idea that fish slime in any way functionally behaves like a polymer additive, the tests did suggest some possible merit in evaluating the rheological characteristics of such slime. In view of the relative ease with which fish slime could be obtained and characterized in the capillary rheometer, limited series of tests were conducted during this program.

The fish slime for these tests was obtained through the cooperation of the Minnesota State Fish Hatchery which supplied the fish and stripped their slime. The fish were native dogfish which had been trapped in nature. Six fish of about 18 in. length were manually squeeze-stroked along their bodies with rubber gloved hands. The stringy slime which accumulated on the gloves was rinsed off in a vessel containing about 1-1/2 gallons of fresh water. This solution was within an hour subjected to shear characterization in the 0.054-in. diameter capillary tube in the same manner as the other additives. The resulting flow curve is shown in Fig. 13; it is comparable to the flow curves for the other test additives and evidences an extensive beneficial region.

A second series of tests was conducted using a fluid consisting of the original slime concentration reduced to one third by dilution with tap water. These data are also plotted in Fig. 13; they, too, show that even the diluted slime solution has marked friction benefit. For reference and comparison, Fig. 13 also includes the flow curves for distilled and sea water and for 0.001 and 0.01 per cent concentrations of Polyhall-27 in sea water.

A further interpretation of these data is given in Fig. 14 which again presents f as a function of the modified Reynolds number N'_{Re} in a manner similar to that of Fig. 8. Figure 14 is significant in that it demonstrates that the friction benefits observed here with fish slime are again seemingly derived from an inherent mechanism which greatly delays the full transition from a laminar to a turbulent boundary layer.

Both Figs. 13 and 14 are also of interest in comparison with Figs. 7 and 8. The more dilute solutions of Figs. 13 and 14 begin a transition to turbulence (point "C" of Fig. 1) at much lower values of 8 V/D and nearly achieve a condition of full turbulence (point "D" of Fig. 1).

The rheological data of Fig. 14 are believed to provide the first significant evidence to support earlier rationalizations [16, 17] that the remarkable performance of swimming fish and mammals must be associated with hydrodynamics processes which lead to extensive laminar boundary layers.

While these data for fish slime lack a definite meaning in terms of concentration effects, they are significant in that the pattern of drag benefit appears quite similar to that of Polyhall-27 in concentrations of about 10 to 50 parts per million. It appears probable that more complete evaluations of the characteristics of fish slime may prove it to be as good or better than any of the commercial additives yet tested.

IV. FRICTION STUDIES IN PIPE SIZE CONDUITS

The single-pass blow-down facility used in the rheometer studies described in the preceding was unsuitable for tests with a sizeable increase in tube diameter, so a pumped recirculating system was set up for the purpose. This system consisted of a smooth-walled stainless steel test section of 1.405 in. inside diameter and a length of 110 diameters. The entrance to this test section was from a concentric 12-in. diameter approach pipe capped with a flat plate normal to the flow axis. The bellmouth transition contraction from the flat plate to the cylindrical test section was the quadrant of an ellipse selected to provide flow contraction without wall separation.

The downstream end of the test section gradually expanded to a 4-in. diameter return pipe followed by an expansion to the 12-in. approach pipe. A variable speed centrifugal pump was mounted in the 4-in. return line and a substantial portion of this line was water jacketed for temperature control.

In accord with the methods of Ref. [1], paired piezometer taps were provided on the tube walls at stations 80, 90, and 100 diameters downstream of the tube entrance. Hydraulic pressure gradient values between these tap stations provided friction data for the evaluation of $D\Delta P/4L$ for test flows through the pipe. The corresponding $8\ V/D$ values were interpreted from discharge measurements using a gravimetric calibration of the pressure differentials across the contraction nozzle. As in Ref. [1], hydraulic gradient studies found that a uniform gradient had been established prior to the first friction measuring station 80 diameters downstream of the entrance.

Friction tests of this character were made at 70° F. for tap water solutions of Polyhall-27 in concentrations of 0.10, 0.01, 0.001, and 0 per cent. The solutions used in these pipe tests differed from those used in the capillaries in that tap water was used rather than sea water and tank batching of the solutions required pumped agitation. As has been shown in the degradation studies of Section III-E5, Polyhall-27 evidenced a sensitivity to shear degradation that raised a question regarding its usefulness in a recirculating system. However, in view of the practical difficulties of working with large test pipes in a one-pass blow-down facility, the use of a recirculating system appeared necessary despite possible degradation influences.

Tap water was used as the solvent in these tests because of the shortage of sea water and because of possible chemical reactions which sea water might have had with the recirculating system. Since previous tests with Polyhall-27 had shown only very slight differences of rheometer friction performance when either distilled water or sea water was used there was no reason to believe that use of tap water would significantly affect the polymer performance in pipe circuit tests.

Logarithmic plots of the friction data for these pipe studies are presented in Fig. 15 in terms of the conventional flow diagram parameters of DΔP/4L vs. 8 V/D. Since it was impractical to measure laminar flows in a pipe as large as this conduit, auxillary laminar flow tests were run in the 0.054-in. capillary tube for the purpose of providing n' and K' characterizations of the test fluids. With these characterizations, the pipe flow data were then interpreted in terms of Fanning's f and Metzner's modified Reynolds number N'_{Re}. The resulting values are plotted in Fig. 16 together with tabulated values of the corresponding n' and K'. The latter values are mean values from samples tested before and after the pipe studies. Some degradation was evident in these tests.

In order to detect possible influences of mechanical degradation during the course of the pipe tests, the test runs have been numbered in the sequence of their occurrence and repeat runs were employed. In the tests of the 0.10 (1000 ppm) concentration, for example, runs were started at the lowest flow speed provided by the variable speed pump, with the test speed progressively increasing from Run 1 to Run 8. For Run 8, audible cavitation occurred at the pump despite the use of the maximum allowable supercharge pressure of 40 psi in the system. Following Run 8, reduced speeds were controlled with a throttling gate valve in the pump discharge line. Runs 9 to 14 constitute progressively lower flow speeds achieved with progressively greater valve throttling. Following throttled Run 14, the valve was opened and check runs 15 and 16 were made at higher pump speeds.

A study of this data sequence indicates that the cavitation which occurred during Run 8 (also presumably some in Run 7) significantly degraded the polymer. On the other hand, the non-cavitating valve throttling conditions appear to have contributed negligible degrading. Similar sequence tests with the 0.01 (100 ppm) and 0.001 (10 ppm) concentrations yielded a somewhat similar pattern of degradation.

A significant feature of the pipe flow tests, as shown in Fig. 16, is the evidence that a flow which is essentially turbulent and comparable to that of the solvent water exists for the low speed pipe flow conditions. This means that the extension of pseudo-laminar conditions, as might be predicted from extrapolating the capillary tube diameter effects to a larger size pipe, has not in fact occurred. It appears instead that some undetermined condition of the fluid or the flow circuit has induced a rather early and full transition to turbulence. It is to be noted that the capillary tube tests involve a quiet, non-vibrating blow-down drive. In contrast, the tunnel pump system, although provided with elastic isolation, did convey disturbance to the test section walls which was evidenced as a small-amplitude low-frequency lateral vibration. Because of the lack of full transition data from either the large blow-down capillaries or the recirculating pump systems, the tests are not definitive with regard to critical transition conditions. It appears, however, that it would be unwise at this time to assume that the low friction pseudo-laminar conditions observed with dilute polymers in blow-down tubes can be safely extrapolated to high Reynolds numbers or to other flow environments. It is possible that solution exposure to copper, zinc, and iron in the flow circuit may have influenced the test fluids.

A second significant feature of the test data in the plot of Fig. 16 is the evidence that friction values for the non-Newtonian solutions are very similar to those of water in the low speed turbulent range, but increasing benefits are shown for the solutions as the speed increases. This appears to be a markedly different pattern than that shown for Curve 7 in Fig. 16 or the more complete pattern of CMC curves shown in Fig. 4. Actually, however, the curve for Polyhall is more realistic than that for CMC in that the latter with its unusual n' and K' values applied through N'_{Re} markedly distorts the relative horizontal position of the test points. This was of course the original Metzner-Reed [5] intent of using N'_{Re} as a correlating parameter as it served to collapse all non-Newtonian data horizontally from right to left until all of the laminar data fell on the common line $f = 16/N'_{Re}$. This manipulation did much to clarify and correlate earlier laminar flow data and it does supply useable f values with proper interpretation of N'_{Re}. Unfortunately, it gives a grossly distorted concept of relative graphical values in the turbulent flow regime because of the large horizontal displacement that occurs with low n' values and high K' values. For example, the highest point shown on Curve 7 of Fig. 16 should be displaced far to the right, so that it falls close to the Karman-Prandtl curve. That this is graphically more realistic may be seen in a study of the original plot of $D\Delta P/4L$ vs. $8\ V/D$ for this fluid (Fig. 4 or Ref. [1]). Such a study discloses that the point D" actually falls very close to the Newtonian turbulent curve DE as shown in Fig. 1. Similarly, it may be noted that the DΔP/4L vs. 8 V/D plots for Polyhall shown in Fig. 15 also place the points corresponding to D" of Fig. 1 upon the DE curve.

Fortunately, the values of n' and K' for the dilute solutions (< 100 ppm) of interest to this program are so close to those of water that relatively little distortion occurs regardless of whether the modified or normal Reynolds number is used.

For additional perspective, related pipe friction data of other investigations have been plotted in Fig. 16. These include the data of Fabula [14] and those of Ousterhout and Hall [18].

Fabula's data were obtained by blow-down tests in a smooth-walled tube of 1.02-cm inside diameter. The additive employed was Polyox-301 and was presumably the same as that used in the evaluations of this program, as treated in Table I and Figs. 7, 8, 10, and 12. Fresh water was used as the solvent. Friction was measured by differential pressure evaluations in the downstream portion of a pipe 750 diameters in length.

Fabula's data include friction values for a wide variety of concentrations, but only the data for concentrations of 13 and 66 ppm have been transferred to Fig. 16 since these roughly approximate the current test concentrations of 0.001 (10 ppm) and 0.01 (100 ppm) per cent. The values of N'_{Re} were calculated using values of n' and K' interpreted from the test results plotted in Fig. 15. While these values of n' and K' are not precise, they are so close to those of water that the latter values could also be taken with very little resulting shift in the plot of Fig. 16.

Comparatively, Fabula's data are noteworthy in that the values for the 66-ppm solution would constitute a fair approximation to the probable extension of the pseudo-laminar data obtained in the current capillary test program (Fig. 8) with both Polyox-301 and Polyhall-27. The data for 13 ppm appear to constitute a transition departure from the pseudo-laminar regime, occurring as a diameter effect, which is in general accord with the pattern of diameter effects observed in the present capillary studies of both Polyox and Polyhall.

The friction data of Ousterhout and Hall were obtained by pumping their test solutions through a 1000 foot length of 2-in. 4.7-lb EUE steel tubing. The test additives are described only as a natural polymer and a synthetic polymer. The data for n' and K' of the solutions were given in the original paper and are shown in the legend of Fig. 16, while the values of f and N'_{Re} were transferred from the paper and plotted in Fig. 16.

It should be noted that comparative interpretation of the curves of Fig. 16 can be meaningful only when the fact is considered that the values of n' and K' for the Ousterhout fluids (Curves 3-6) are greatly different from those for water and the other fluids involved. Direct graphical comparison would be feasible if Curves 3-6 were correspondingly elongated and shifted far to the right.

The synthetic polymer data of Ousterhout and Hall are noteworthy in that they again indicate the probable further extension of the pseudo-laminar regime, with increasing pipe diameter, to still higher values of N'_{Re}, and the eventual tendencies toward a slow transition to turbulence.

The values of n' and K' for the natural polymer solution (Fig. 16) indicate that also this solution is much different from water under laminar conditions, and the values are somewhat comparable to those involved in the tests relating to Fig. 4. Accordingly, the turbulent data from Fig. 4 pertaining to the 0.01 and 0.75 concentrations of CMC have also been transferred to Fig. 16 for comparison purposes. It appears from this that the natural polymer of Ousterhout and Hall acts very much in accord with CMC at comparable n' values, although such n' for the former is achieved with only a fraction of the additive concentration employed for CMC. Careful study of Curves 5, 6, and 8 suggests that all of these curves probably represent turbulent curves which should be elongated and displaced far to the right for correct perspective.

It is interesting to note that the tests of Ousterhout and Hall were conducted in rough pipe, as evidenced by their comparison of the water flow data with accepted Newtonian smooth pipe data.

V. CONCLUSIONS

Dilute sea water solutions of the long chain polymers Polyhall-27 and to some extent of Polyox-301 have been studied with respect to their relative efficiency in reducing boundary friction in cylindrical conduit type flows within the range of Reynolds number N'_{Re} from 10^2 to 10^6 and of tube diameter ratios from 1 to 100. The additives studied were selected as superior to a variety of other additives on the basis of a limited screening test. The study has systematically varied the additive concentration, the fluid temperature, the shear rate, and the conduit diameter. The following conclusions may be tentatively drawn with regard to the influence of these test variables on boundary friction with these fluids.

1. Qualitative comparative frictional benefits evidenced in conduit flows involving the addition of long chain polymers are realistically portrayed by logarithmic plottings of $D\Delta P/4L$ vs. $8\ V/D$ although such plottings are of limited usefulness in general boundary layer studies.

2. Graphical representation of frictional values using the f of Fanning and the modified Reynolds number, N'_{Re}, of Metzner-Reed provides a convenient qualitative measure. However, the latter parameter does not effectively correlate dilute polymer data and it leads to unrealistic graphical comparison of fluids with wide ranging value of n' and K'. Despite this, the parameter is still the most effective available index.

3. On the basis of the above two considerations, it is deemed advisable to emphasize in these conclusions the results in terms of the second representation (f vs. N'_{Re}) while using the first representation for clarification.

4. The Fanning Friction Factor f is approximated by the expression $f = 16/N'_{Re}$ for $200 < N'_{Re} < 1200$.

5. Departure from fully laminar flow appears to occur somewhere in the range of N'_{Re} from 1000 to 1500. This seems to be true for Newtonian water as well as for the non-Newtonian solutions.

6. Transition from fully laminar flow to fully turbulent flow evidently occurs in at least two phases. The first phase is a gradual departure from the laminar state, with f values progressively increasing above those represented by $f = 16/N'_{Re}$. This first phase may occur over a range of N'_{Re} varying from small to large, depending on the type of fluid and the flow conditions. This phase is manifested by near-laminar or pseudo-laminar flow effects. The second phase is usually marked by a fairly rapid increase in f values, and a fairly narrow range of N'_{Re} serves to complete the transition from the pseudo-laminar condition to the fully turbulent condition. The second phase is characterized by large-scale low-frequency flow fluctuations or instability.

7. For Newtonian fluids, the first phase of transition covers a narrow range of N'_{Re} from about 1000 to 2100, with only a very modest increase in f above the values given by the equation $f = 16/N'_{Re}$. The second phase also generally covers a fairly narrow range of N'_{Re} beginning at 2100 and ending between 3000 and 4000.

8. For the smooth tubes tested, data for the Newtonian fluids in the turbulent range make the usual approximate fit with Eq. (4) of Blasius. A better fit is achieved with Eq. (5) of Karman-Prandtl. All of the current non-Newtonian test data fall below these indices of turbulence. Projection of the Blasius equation to its intersection with $f = 16/N'_{Re}$ establishes the intersection at an N'_{Re} value of 1200, which is the approximate value at which fully laminar flow was observed to cease.

9. For non-Newtonian fluids in general, the pseudo-laminar or first phase of transition begins around $N'_{Re} = 1000$ or 1500, as with Newtonian fluids, but ends at values

somewhat higher than those for Newtonian fluids. While most previous tests of non-Newtonians have shown this departure to occur at little more than $N'_{Re} = 4000$, these tests with water-like solutions indicate that pseudo-laminar conditions can be readily maintained to at least $N'_{Re} = 50,000$ and probably in excess of 100,000.

10. The limiting f values for pseudo-laminar conditions with the new dilute solutions are conservatively represented by the equation $f = 1.5/(N'_{Re})^{2/3}$. For the very dilute solutions, f values substantially lower than those given by this equation may be observed at lower values of N'_{Re}. This equation has been selected to intersect also the equation $f = 16/N'_{Re}$ at $N'_{Re} = 1200$.

11. Second phase transition from the pseudo-laminar curve $f = 1.5/(N'_{Re})^{2/3}$ to the turbulent curve $f = .079/(N'_{Re})^{1/4}$ occurs as some function of the concentration, temperature, and tube diameter. The form of this function is not clearly defined by the available data, but it is definitely not associated with a constant N'_{Re} as for Newtonian fluids. It appears that the pattern of second phase transition for very dilute solutions ($\approx$10 ppm) is longer and more gradual than that for higher concentrations. The difference is believed to be associated with the critical concentrations observed by Fabula [14]. Higher concentrations and/or larger diameters delay the second phase transition to unusually high values of N'_{Re}.

12. The magnitudes n' and K' for dilute Polyhall and Polyox solutions are fairly close to those of water, and the values for Polyhall proved to be constant throughout the range of shearing conditions employed in these tests. In this respect, these solutions are not shear thinning or pseudo-plastic, unlike the more

concentrated solutions.

13. The values of n' and K' for Polyhall and Polyox solutions of 100 ppm or less are so close to those of the solvent water that, for all practical purposes, those for water may be used instead to simplify the calculations of Reynolds numbers. The modified Reynolds number N'_{Re} thus has no significance in correlating tests for these dilutions.

14. For the materials used in these tests, Polyhall-27 provided a somewhat lower f value than Polyox-301 in most of the pseudo-laminar range, but Polyox-301 persisted in a pseudo-laminar regime to significantly greater values of N'_{Re}.

15. Temperature appeared to have relatively little influence on the value of f in the pseudo-laminar regime, but in general persistence of the pseudo-laminar flow regime was extended with temperature increase.

16. Shear friction values for Polyhall-27 and Polyox-301 solutions appear to change very little regardless of whether sea water or fresh water is used as the solvent.

17. Both Polyhall-27 and Polyox-301 solutions evidenced significant mechanical shear degradation. This sensitivity is believed to pose no serious problem in single pass expendable use in practice, provided severe shear exposure does not occur in mixing or distribution.

18. The non-Newtonian tests in a recirculating, pumped, pipe-size system gave an unaccountably early transition to full Newtonian turbulence, thus casting some doubt on the stability of the extremely delayed transitions observed in smaller blow-down test conduits.

19. A seemingly new form of rapidly decreasing wall shear with increasing shear rate has been observed at high Reynolds numbers ($N'_{Re} \approx 10^6$) with these dilute solutions. An earlier and steeper decline in wall shear values occurs with increasing solution concentration.

20. While the more concentrated polymer solutions appear (Figs. 3 and 4) to give sustained friction benefits throughout the turbulent water range when treated as a function of N'_{Re}, this interpretation is actually distorted. Actual operations probably involve a plateau of zero benefits in some middle turbulent range.

21. Dilute solutions of the slime from Dogfish produce the same remarkable pseudo-laminar friction reducing benefits as the dilute long-chain polymers. This finding materially strengthens earlier rationalizations that fish performance must somehow be associated with boundary layers which are laminar to an unusual extent.

LIST OF REFERENCES

[1] Ripken, J. F. and Pilch, M. Studies of the Reduction of Pipe Friction with the Non-Newtonian Additive CMC, University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Technical Paper No. 42, Series B, April 1963.

[2] Deb, S. K. and Mukherjee, S. N. "Molecular Weight and Dimensions of Guar Gum from Light Scattering in Solution," Indian Journal of Chemistry, October 1963.

[3] Symposium on Non-Newtonian Viscometry, American Society for Testing and Materials Special Technical Publication No. 299, 1962.

[4] Porter, R. S., Cantow, M. J. R., and Johnson, J. F. "Sonic Degradation of Polyisobutylene in Solution," Journal of Applied Physics, Vol. 35, No. 1, January 1964.

[5] Metzner, A. B. and Reed, J. C. "Flow of Non-Newtonian Fluids--Correlation of the Laminar, Transition, and Turbulent-Flow Regions," Journal American Institute of Chemical Engineers, Vol. 1, 1955.

[6] Dodge, D. W. and Metzner, A. B. "Turbulent Flow of Non-Newtonian Systems," Journal American Institute of Chemical Engineers, Vol. 5, June 1959.

[7] Shaver, R. G. and Merrill, E. W. "Turbulent Flow of Pseudoplastic Polymer Solutions in Straight Cylindrical Tubes," Journal American Institute of Chemical Engineers, Vol. 5, June 1959.

[8] Metzner, A. B. "Flow of Non-Newtonian Fluids," in Handbook of Fluid Dynamics, Edited by Streeter, McGraw-Hill Book Company, 1961.

[9] Bogue, D. C. "Entrance Effects and Prediction of Turbulence in Non-Newtonian Flow," Industrial and Engineering Chemistry, July 1959.

[10] Dorsey, N. E. Properties of Ordinary Water Substance, Reinhold Publishing Corporation, 1940.

[11] Hawley, S. A., Macleod, R. M., and Dunn, F. "Degradation of DNA by Intense, Noncavitating Ultrasound," Journal Acoustical Society of America, August 1963.

[12] Merrill, E. W., Ram, A., and Mickley, H. S. "Degradation of Polymers in Solution Induced by Turbulence and Droplet Formation," Journal of Polymer Science, Vol. 62, December 1962.

[13] Crawford, H. C. and Pruitt, G. T. Rheology and Drag Reduction of Some Dilute Polymer Solutions, A Report by Westco Research, The Western Company of North America, July 1962.

[14] Fabula, A. G. The Toms Phenomenon in the Turbulent Flow of Very Dilute Polymer Solutions, Fourth International Congress on Rheology, Providence, Rhode Island, August 1963.

[15] Kempf, G. and Neu, W. "Schleppversuche mit Hecten zur Messung des Wasserwiderstandes," Z. der vergleichenden Physiologie, 1932.

[16] Gero, D. R. "The Hydrodynamic Aspects of Fish Propulsion," American Museum Novitates, December 11, 1952.

[17] Lang, T. G. and Daybell, D. A. Porpoise Performance Tests in a Salt Water Tank, U. S. Naval Ordnance Test Station, T. P. 3063, January 1963.

[18] Ousterhout, R. S. and Hall, C. B. "Reduction of Friction Loss in Fracturing Operations," Journal of Petroleum Technology, March 1961.

FIGURES

(1 through 16)

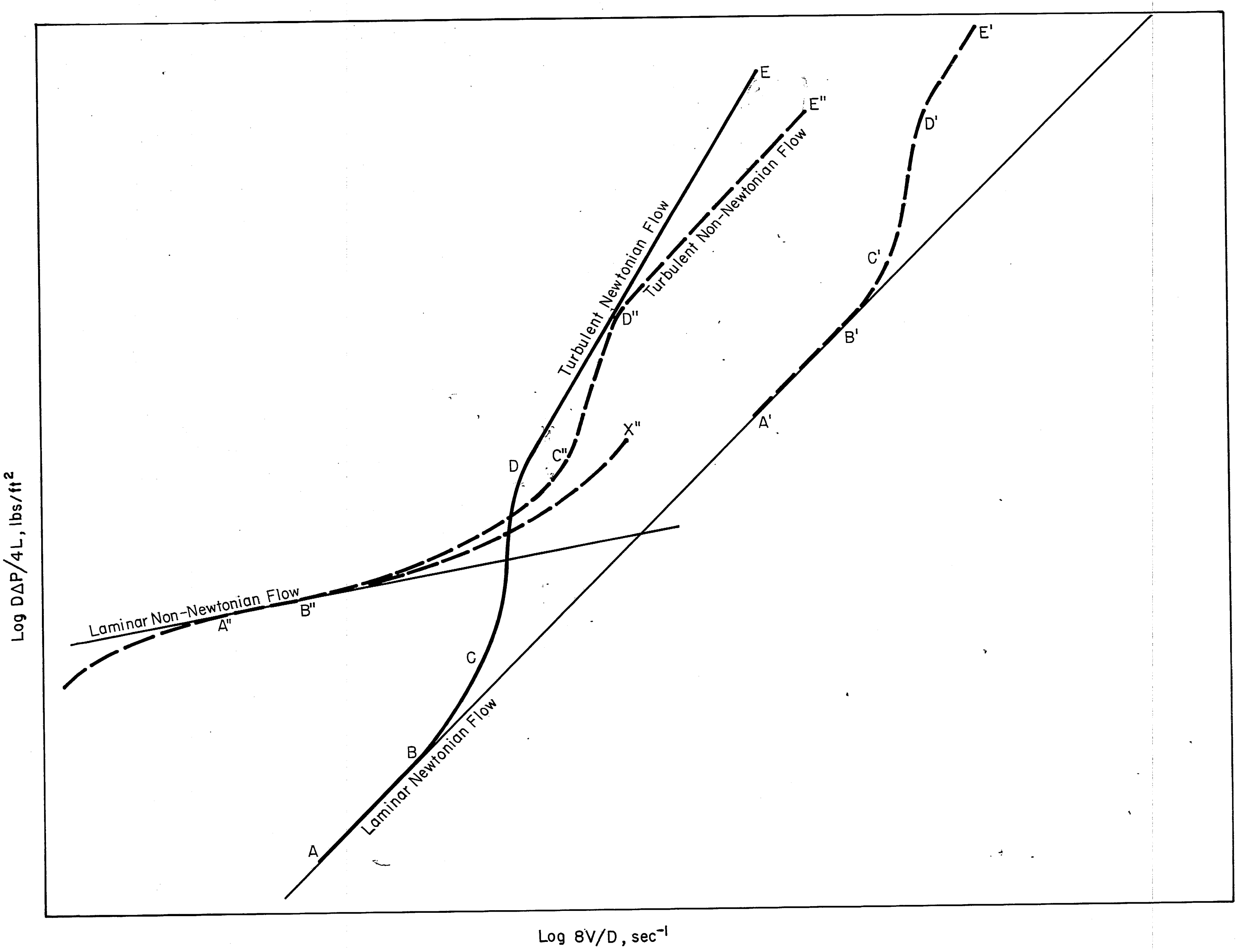


Fig. 1 - Typical Flow Curves for a Newtonian and a Pseudoplastic Non-Newtonian Fluid

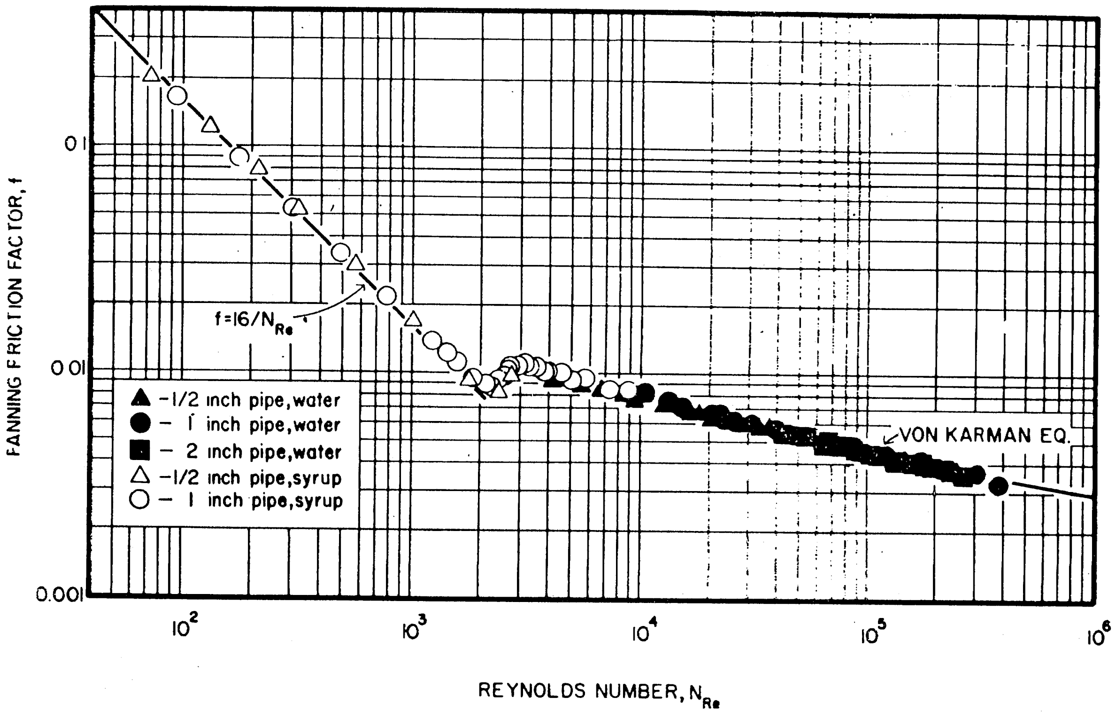


Fig. 2 - A Typical Graphical Correlation of Smooth Pipe Friction Factors vs. Reynolds Number for Newtonian Fluids (from Ref. 6)

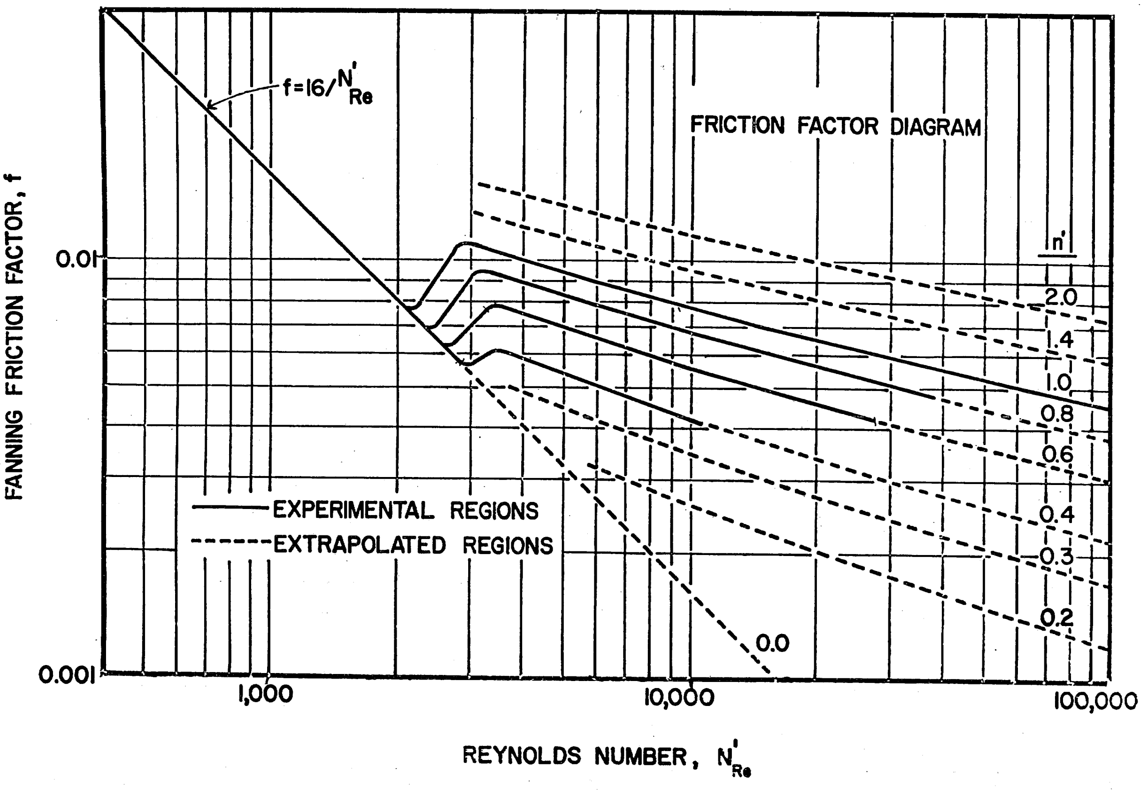


Fig. 3 - Graphical Correlation of Smooth Pipe Friction Factors vs. a Modified Reynolds Number for Several Common Non-Newtonian Fluids with n' Between 0.36 and 0.73 (from Ref. 6)

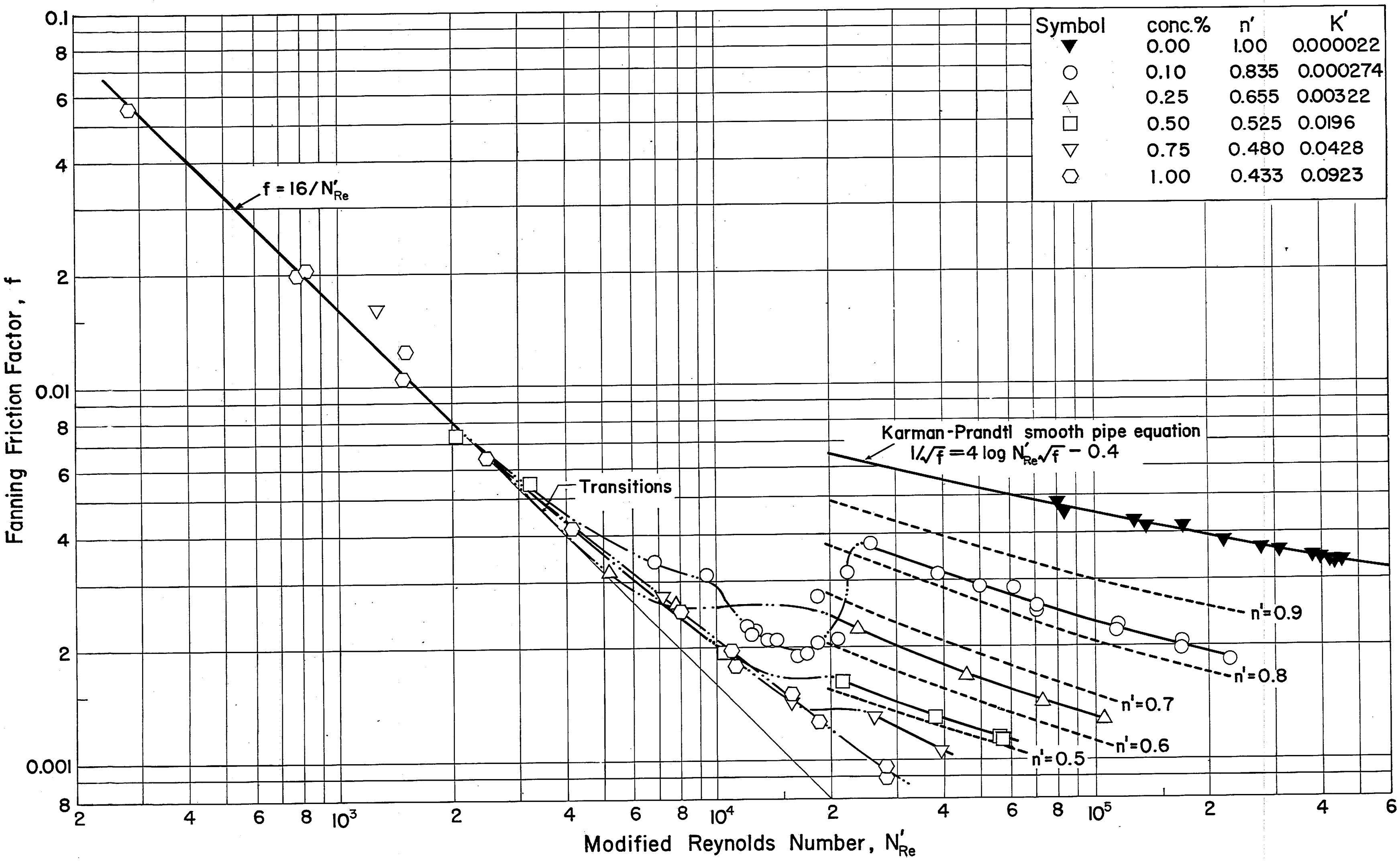
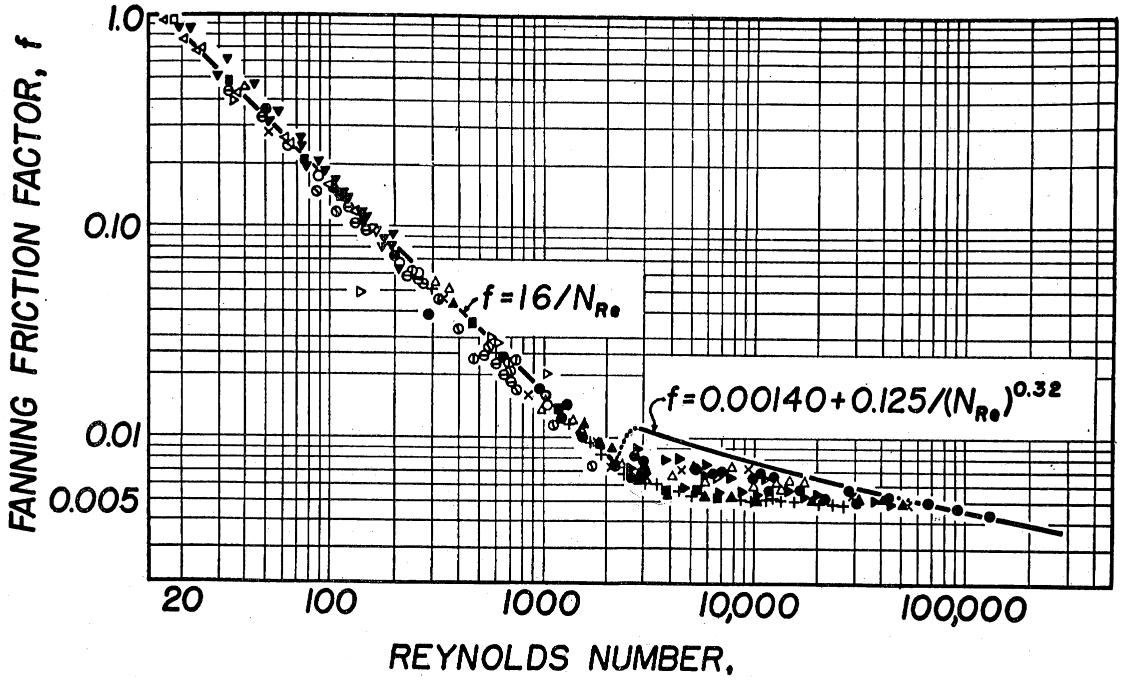


Fig. 4 - Friction Factor f vs. Reynolds Number N'_{Re} for a Smooth Pipe of 0.902-in. Diameter with Various Fresh Water Solutions of CMC-7HSCP at 70° F (from Ref. 1)



Friction factor–Reynolds number diagram for non-Newtonians–high range.

Symbol used in figures	Nominal pipe size, in.	Composition of fluid	n'
+	1	23.3% Illinois yellow clay in water	0.229
⦶	⅞ and 1½	0.67% carboxy-methyl-cellulose (CMC) in water	0.716
⊖	⅞ and 1½	1.5% CMC in water	0.554
⊘	⅞ and 1½	3.0% CMC in water	0.566
⦸	⅞, 1½, and 2	33% lime water	0.171
◁	⅞ and 1½	10% napalm in kerosene	0.520
▼	8, 10, and 12	4% paper pulp in water	0.575
△	¾ and 1½	54.3% cement rock in water	0.153
▲	4	18.6% solids, Mississippi clay in water	0.022
●	¾ and 1¼	14.3% clay in water	0.350
▷	¾ and 1¼	21.2% clay in water	0.335
×	¾ and 1¼	25.0% clay in water	0.185
▽	¾ and 1¼	31.9% clay in water	0.251
□	¾ and 1¼	36.8% clay in water	0.176
■	¾ and 1¼	40.4% clay in water	0.132
▶	⅛, ¼, ½	23% lime in water	0.178

Fig. 5 - Graphical Laminar Flow Correlation of Smooth Pipe Friction Factors vs. a Modified Reynolds Number for Fluids, Including High Concentrations of Suspended Minerals (from Ref. 5)

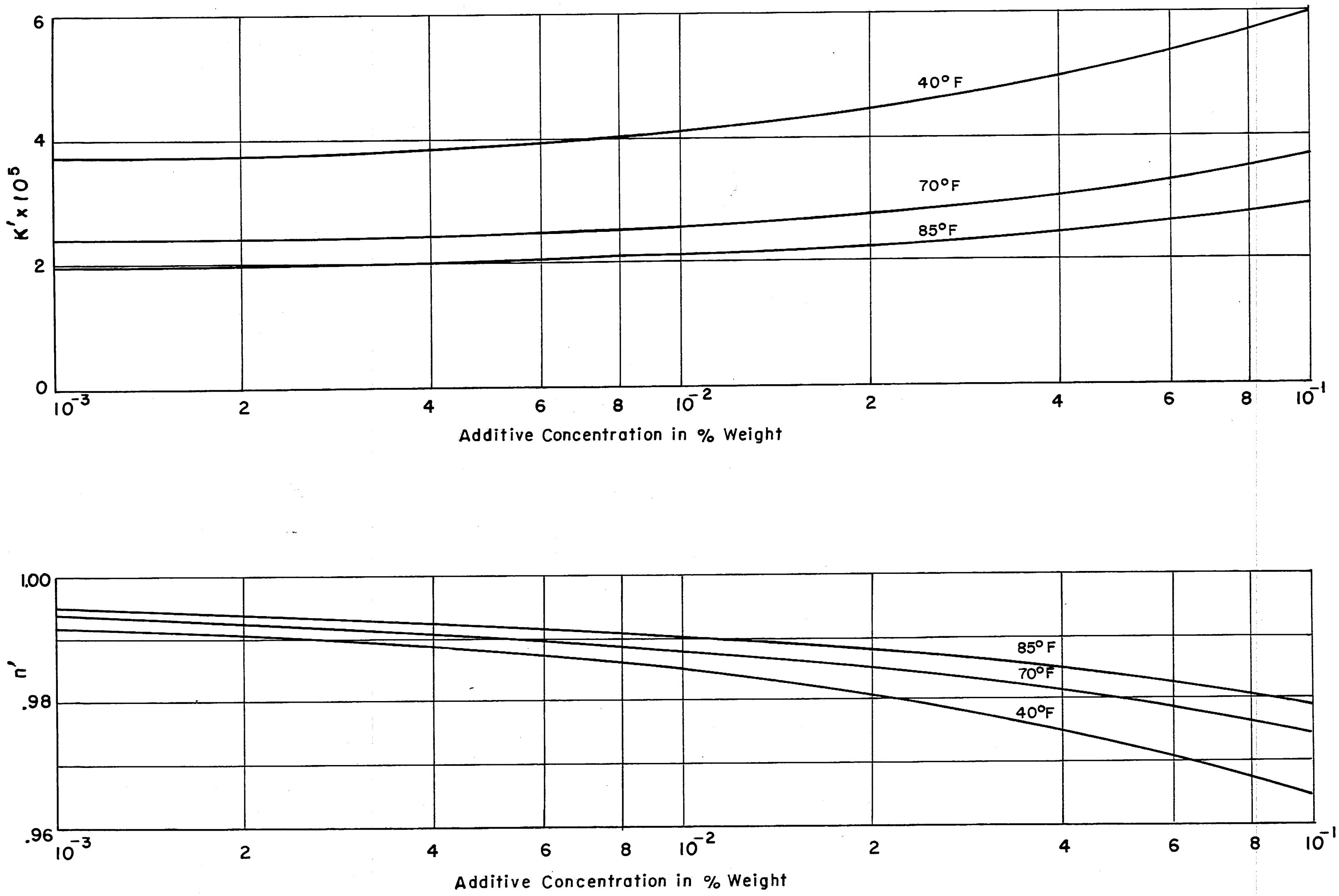


Fig. 6 - Values of n' and K' for Polyhall-27 in Sea Water at Various Dilute Concentrations and Temperatures

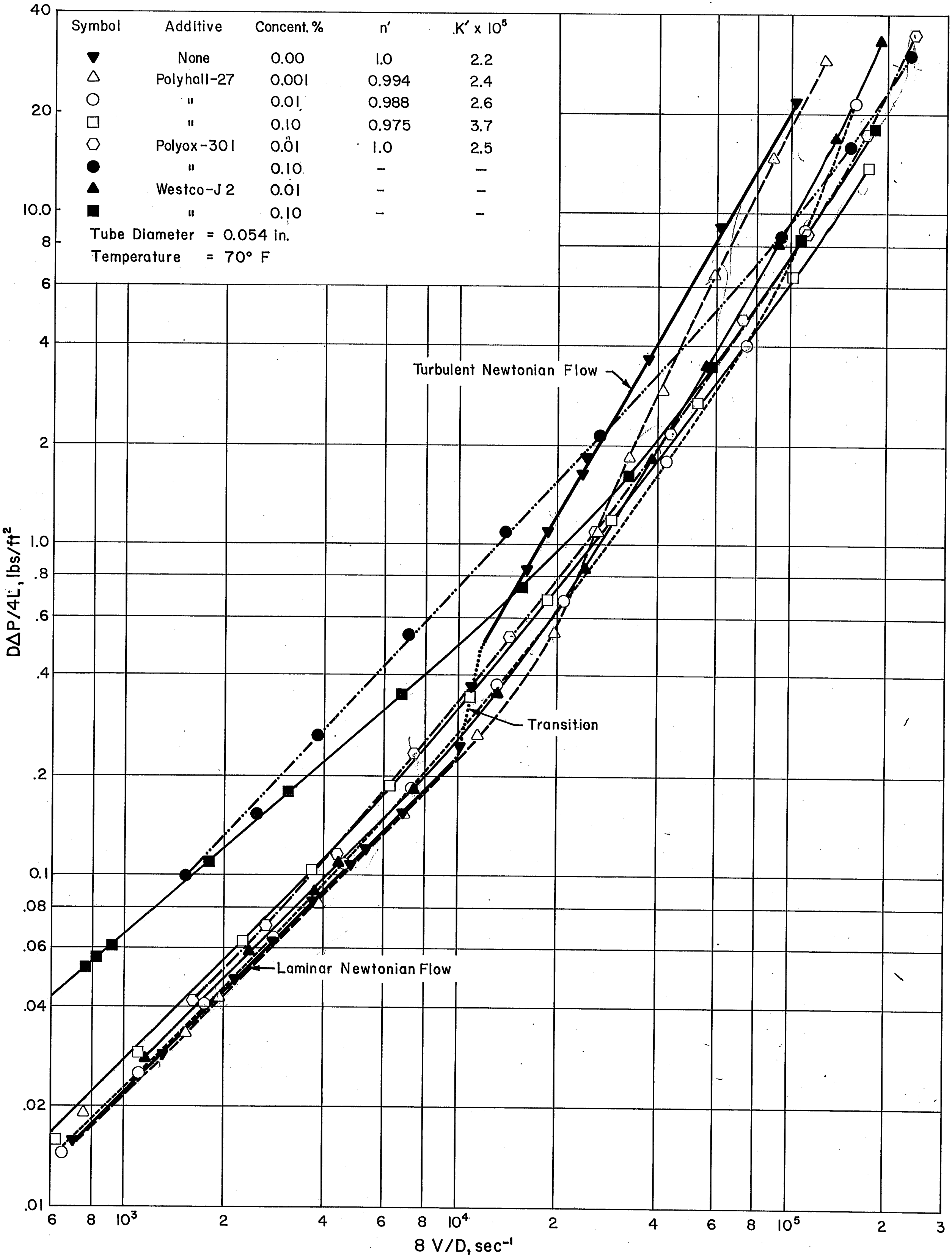


Fig. 7 - Comparative Capillary Wall Shear Values for Sea Water and Solutions of Polyhall-27, Polyox-301, and Westco-J2

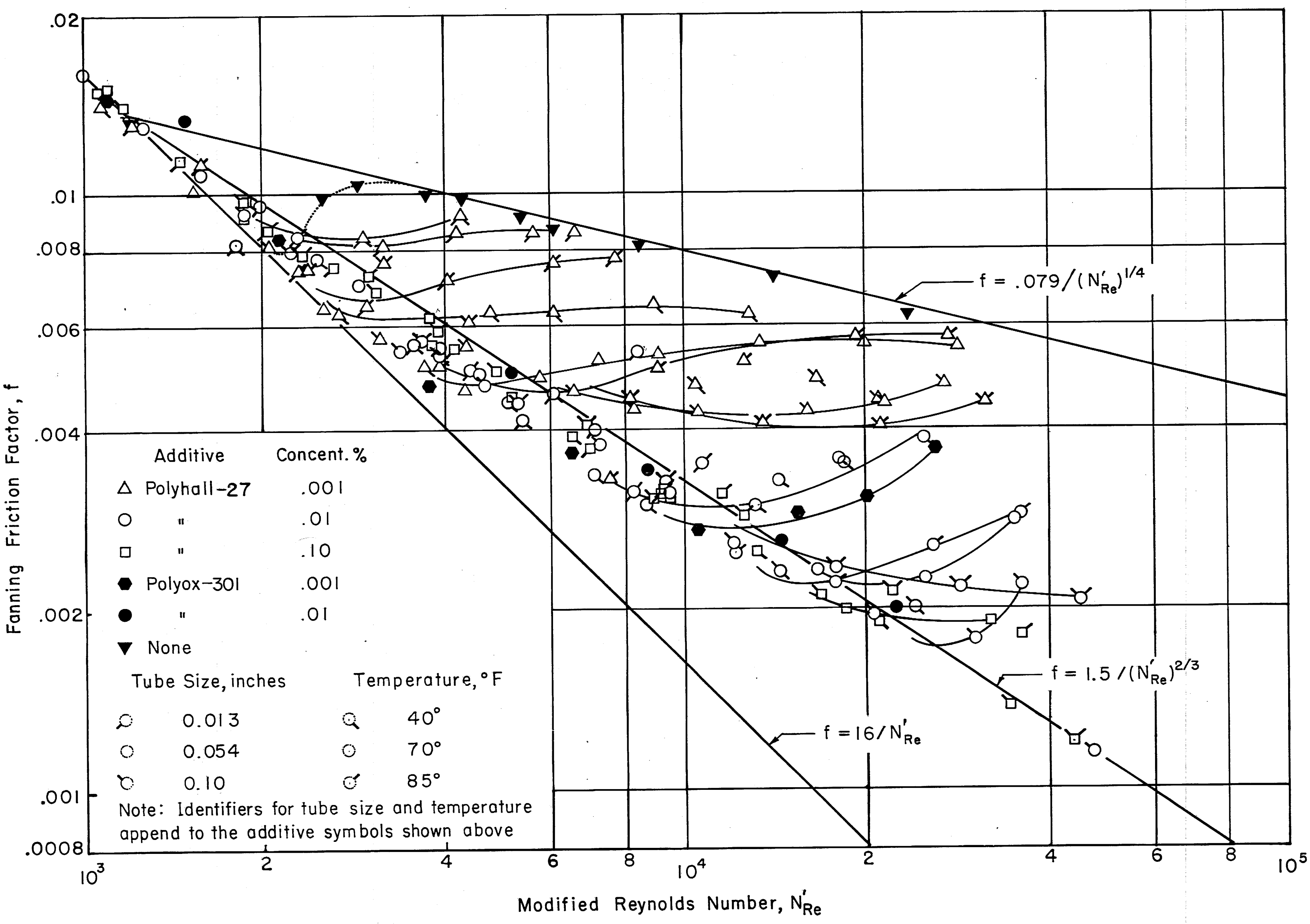


Fig. 8 - Smooth Capillary Tube Friction Factors vs. a Modified Reynolds Number for Dilute Sea Water Solutions of Polyhall-27 and Polyox-301 (on the basis of laminar flow correlation)

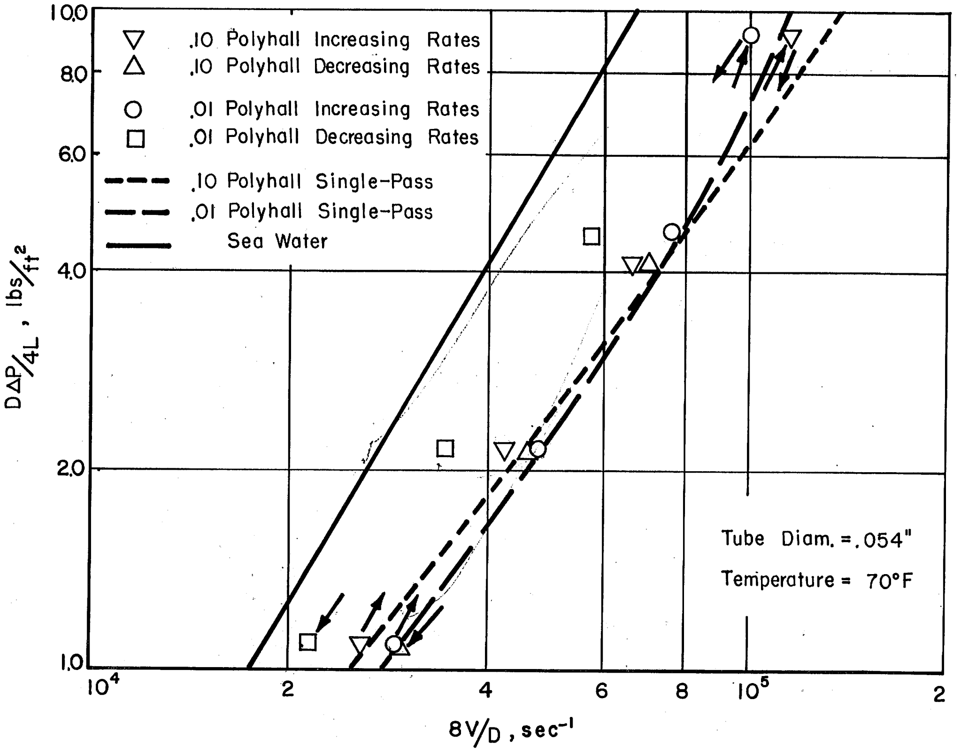


Fig. 9 - Shear Degradation Tests of Polyhall-27 Solutions by Repeated Flow Through a Capillary Tube

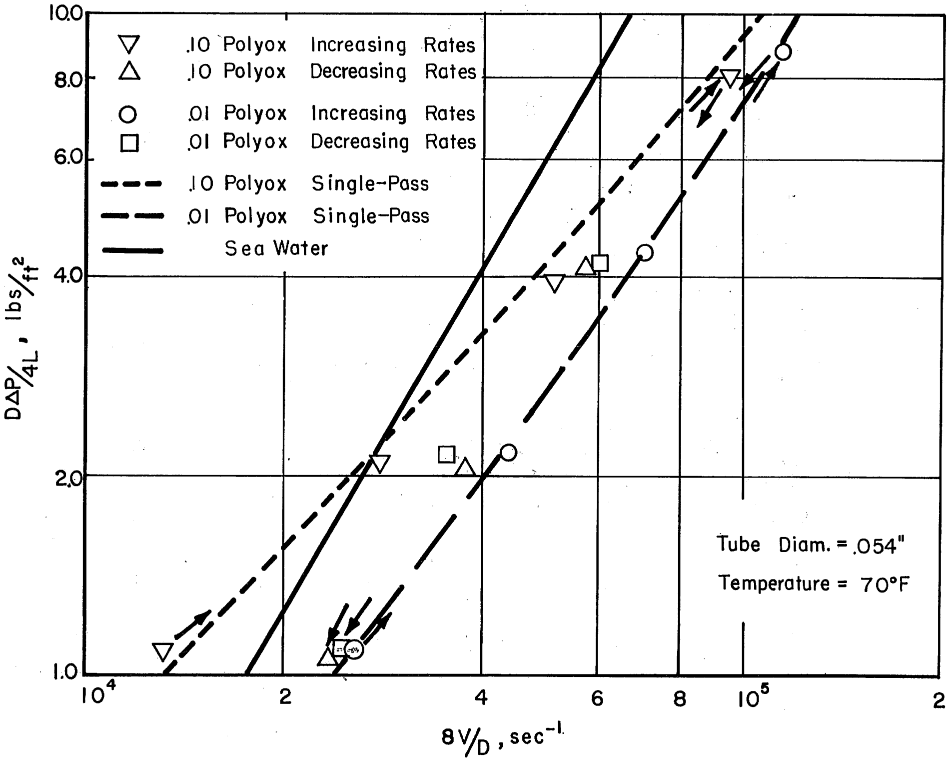


Fig. 10 - Shear Degradation Tests of Polyox-301 Solutions by Repeated Flow Through a Capillary Tube

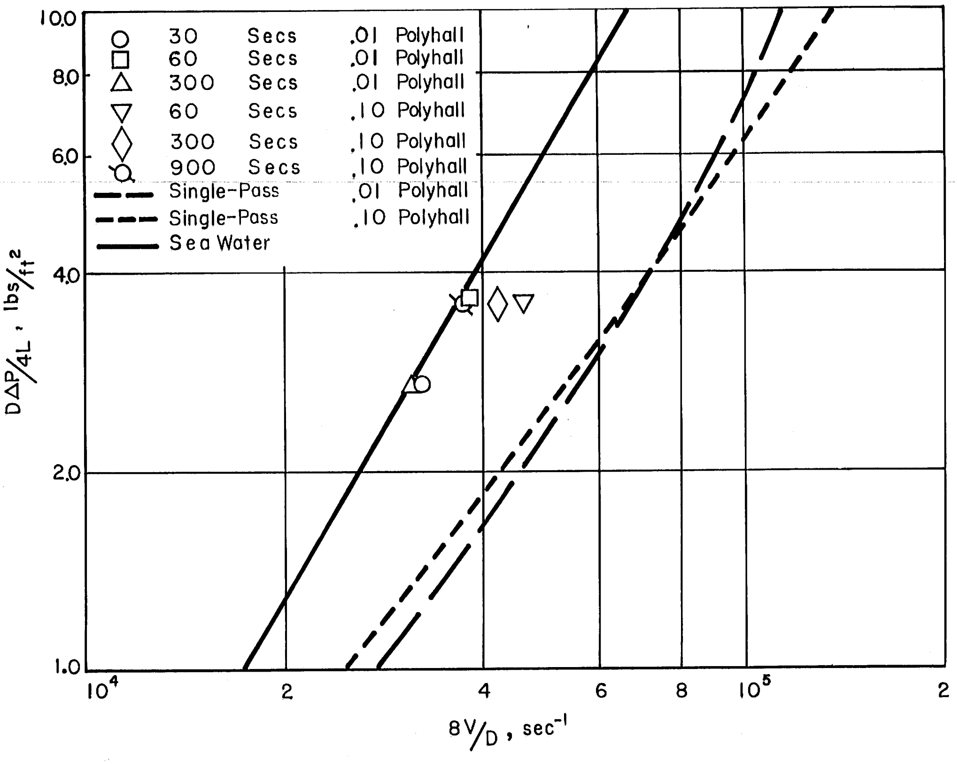


Fig. 11 - Shear Degradation Tests of Polyhall-27 Solutions in a Waring Blender

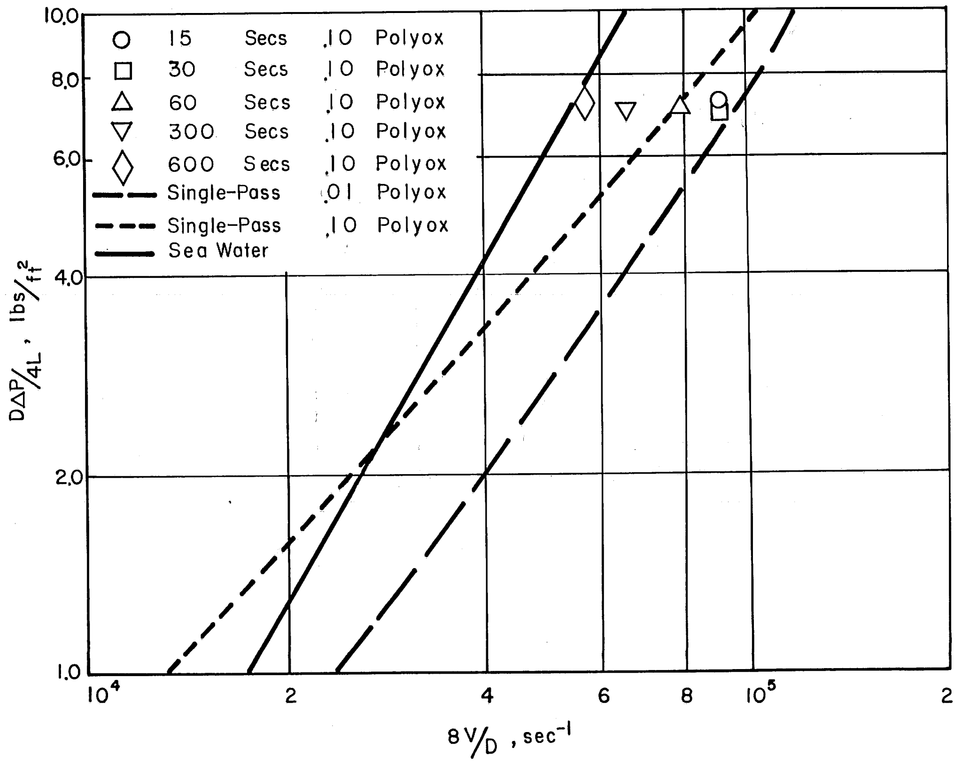


Fig. 12 - Shear Degradation Tests of Polyox-301 Solutions in a Waring Blender

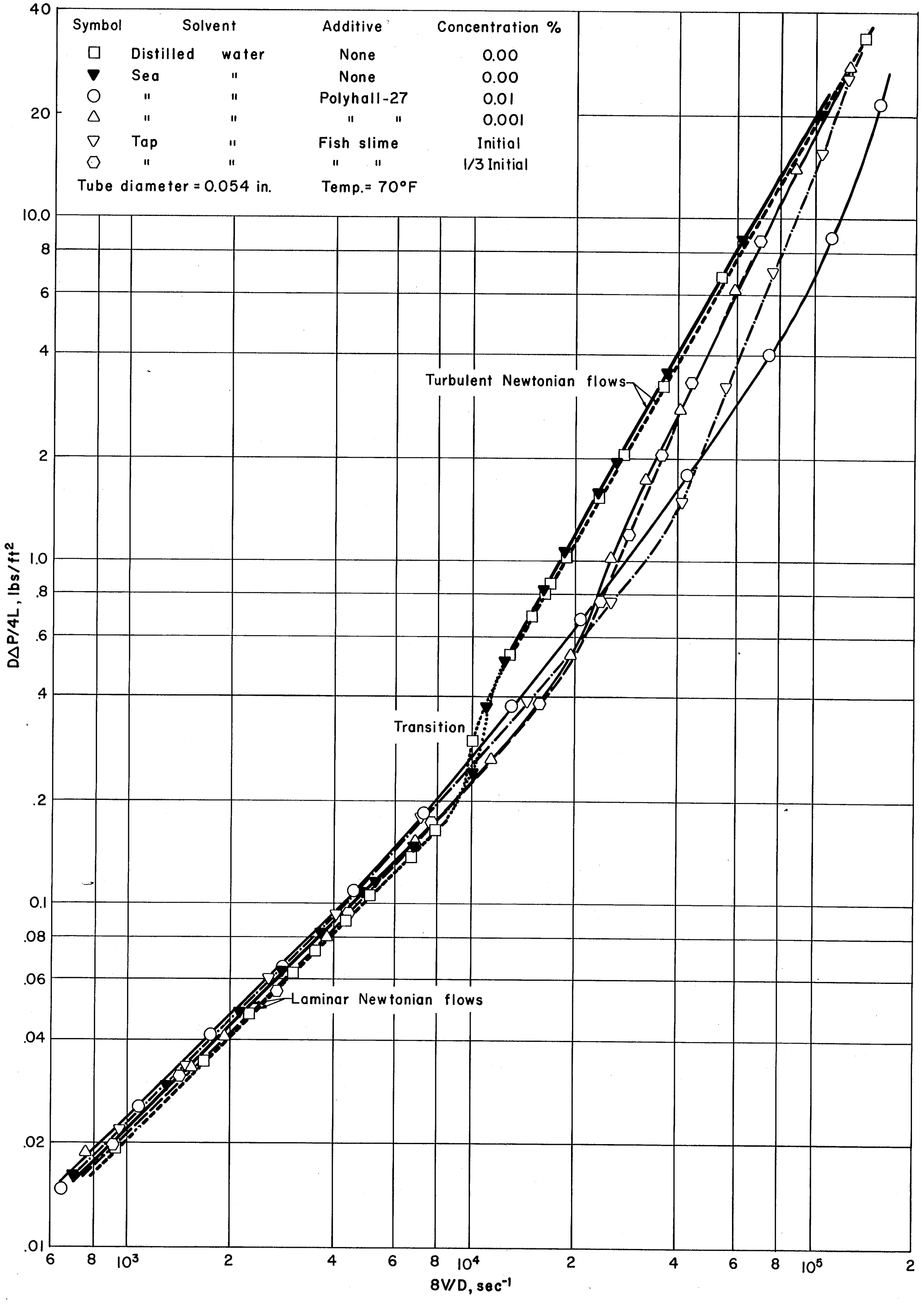


Fig. 13 - Comparative Capillary Wall Shear Values for Water and Solutions of Polyhall-27 and Dogfish Slime

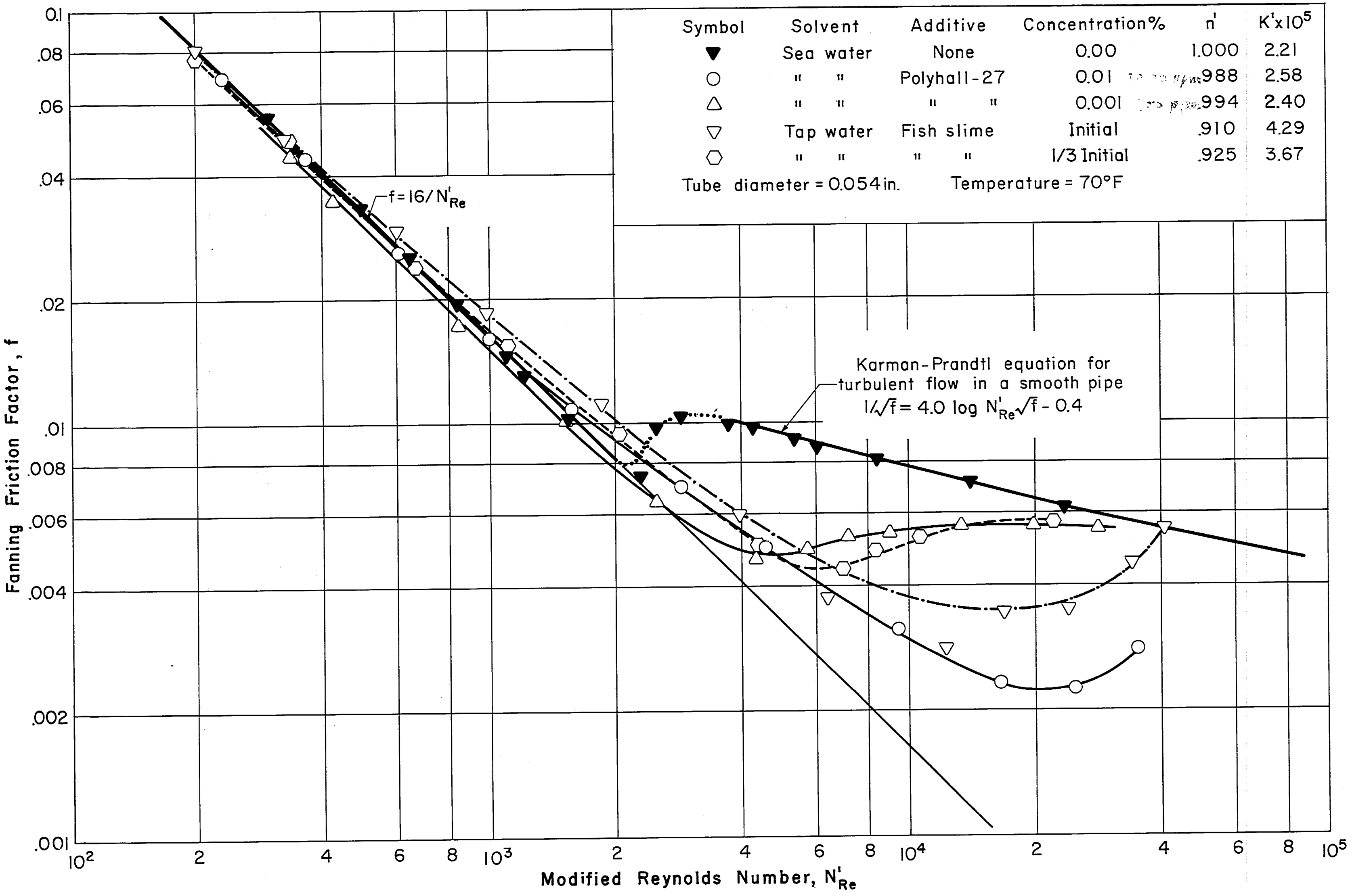


Fig. 14 - Comparative Capillary Friction Values for Water and Solutions of Polyhall-27 and Dogfish Slime

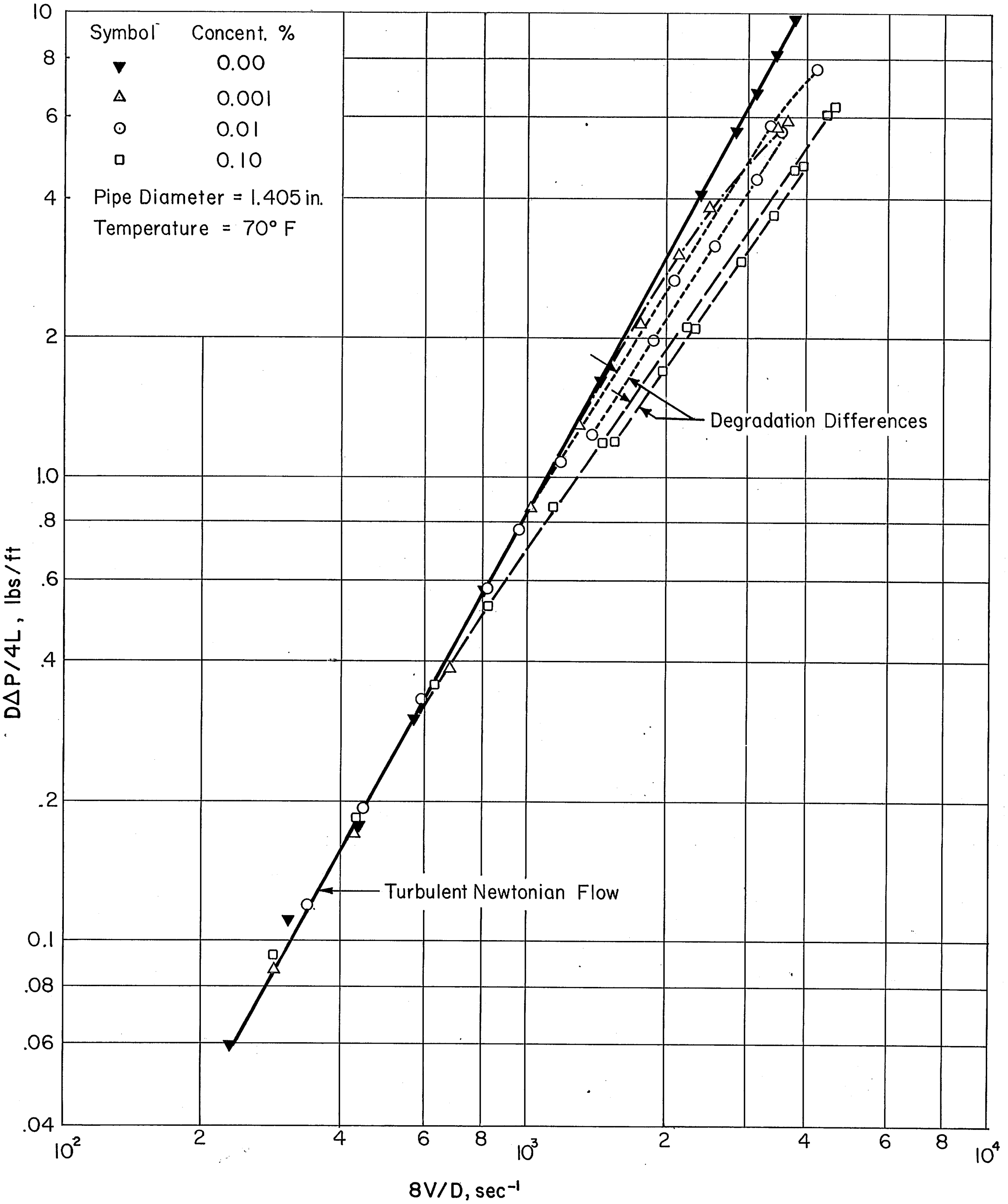
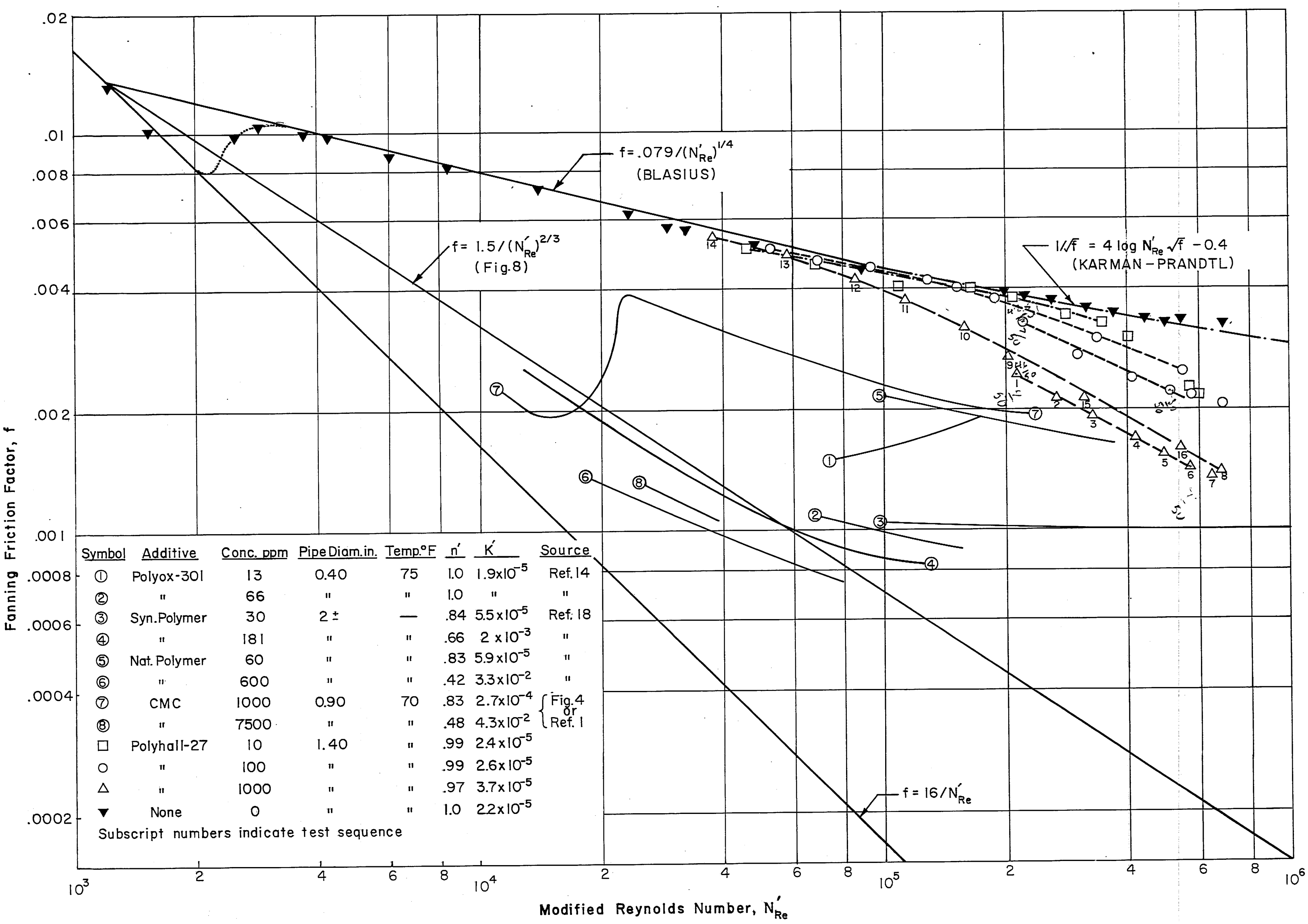


Fig. 15 - Wall Shear Values for Polyhall-27 Solutions in a Pipe Size Conduit



Symbol	Additive	Conc. ppm	Pipe Diam. in.	Temp. °F	n'	K'	Source
①	Polyox-301	13	0.40	75	1.0	1.9×10^{-5}	Ref. 14
②	"	66	"	"	1.0	"	"
③	Syn. Polymer	30	2 ±	—	.84	5.5×10^{-5}	Ref. 18
④	"	181	"	"	.66	2×10^{-3}	"
⑤	Nat. Polymer	60	"	"	.83	5.9×10^{-5}	"
⑥	"	600	"	"	.42	3.3×10^{-2}	"
⑦	CMC	1000	0.90	70	.83	2.7×10^{-4}	Fig. 4 or Ref. 1
⑧	"	7500	"	"	.48	4.3×10^{-2}	
□	Polyhall-27	10	1.40	"	.99	2.4×10^{-5}	
○	"	100	"	"	.99	2.6×10^{-5}	
△	"	1000	"	"	.97	3.7×10^{-5}	
▼	None	0	"	"	1.0	2.2×10^{-5}	

Subscript numbers indicate test sequence

Fig. 16 – Friction Factor vs. a Modified Reynolds Number for Pipe Size Tests of Solutions of Polyhall-27 and other Additives

DISTRIBUTION LIST FOR PROJECT REPORT NO. 71
of the St. Anthony Falls Hydraulic Laboratory

Copies	Organization
65	Commanding Officer and Director, David Taylor Model Basin, Washington 7, D. C., Attn: Code 513.
9	Chief, Bureau of Ships, Department of the Navy, Washington 25, D. C., Attn: 3 - Technical Library 1 - Preliminary Design (Code 420) 1 - Hull Design (Code 440) Development 1 - Research and Planning (Code 330) 1 - Hydromechanics, Logistics, and Special Craft (Code 341B) 1 - Ship Silencing (Code 345) 1 - Laboratory Management Division (Code 320)
6	Chief, Bureau of Yards and Docks, Department of the Navy, Washington 25, D. C.
6	Chief, Bureau of Naval Weapons, Department of the Navy, Washington 25, D. C., Attn: Underwater Ordnance (Code Re6a). 3 - RU 3 - RAAD
3	Chief of Naval Research, Department of the Navy, Washington 25, D. C., Attn: Fluid Dynamics Branch (Code ONR 438).
1	Director, U. S. Naval Research Laboratory, Washington 25, D. C., Attn: Code 2021.
1	Commanding Officer, Office of Naval Research, Branch Office, 230 North Michigan Avenue, Chicago 1, Illinois.
1	Commander, U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland.
3	U. S. Naval Ordnance Test Station, 3202 East Foothill Boulevard, Pasadena, California, Attn: 1 - Commander 1 - Dr. J. W. Hoyt 1 - Mr. A. G. Fabula
1	Commanding Officer and Director, U. S. Navy Underwater Sound Laboratory, Fort Trumbull, New London, Connecticut.
2	Director, Ordnance Research Laboratory, Pennsylvania State University, University Park, Pennsylvania.

Copies	Organization
1	Superintendent, U. S. Naval Postgraduate School, Monterey, California, Attn: Librarian.
1	Assistant Secretary of the Army, (Research and Development), Department of the Army, Washington 25, D. C.
1	Director, U. S. Waterways Experiment Station, Corps of Engineers, P. O. Box 631, Vicksburg, Mississippi, Attn: Technical Librarian.
1	Office of the Chief of Engineers, Civil Works, Department of the Army, Gravelly Point, Washington 25, D. C.
1	Director of Research, National Aeronautics and Space Administration, 1520 H Street, N. W., Washington 25, D. C.
1	Director, Langley Aeronautical Laboratory, National Aeronautics and Space Administration, Langley Field, Virginia.
1	Director, Hydraulic Laboratory, Bureau of Reclamation, Denver Federal Center, Denver, Colorado.
20	Defense Documentation Center for Scientific and Technical Information, Arlington Hall Station, Arlington 12, Virginia.
2	Director, National Bureau of Standards, National Hydraulic Laboratory, Washington 25, D. C.
2	Newport News Shipbuilding and Dry Dock Company, Newport News, Virginia, Attn: 1 - Assistant Naval Architect 1 - Director, Hydraulic Laboratory
1	California Institute of Technology, Division of Engineering, Pasadena 4, California.
2	Director, Davidson Laboratory, Stevens Institute of Technology, 711 Hudson Street, Hoboken, New Jersey.
1	Director, Hydraulic Laboratory, Worcester Polytechnic Institute, Worcester 2, Massachusetts.
1	Director, Hydrodynamics Laboratory, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.
1	Head, Department of Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.
1	Director, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts.

Copies	Organization
1	Director, Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Iowa.
1	Hydronautics, Incorporated, Pindell School Road, Laurel, Maryland, Attn: Mr. Phillip Eisenberg.
1	Western Company of North America, 1171 Empire Central, Dallas 7, Texas, Attn: Dr. H. R. Crawford.
1	Department of Chemical Engineering, University of Delaware, Newark, Delaware, Attn: Dr. A. B. Metzner.
1	Director, Engineering Societies Library, 29 West 39th Street, New York 18, New York.
2	Library, California Institute of Technology, Pasadena, California.
1	Librarian, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.
1	Librarian, School of Engineering, University of Texas, Austin, Texas.
3	Serials Division, University of Minnesota Library, Minneapolis, Minnesota 55455.