NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20034

Report 3994

PROGRESS IN FRICTIONAL DRAG REDUCTION - SUMMER 1971 TO SUMMER 1972

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by

Paul S. Granville

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Naval Ship Research and Development Center
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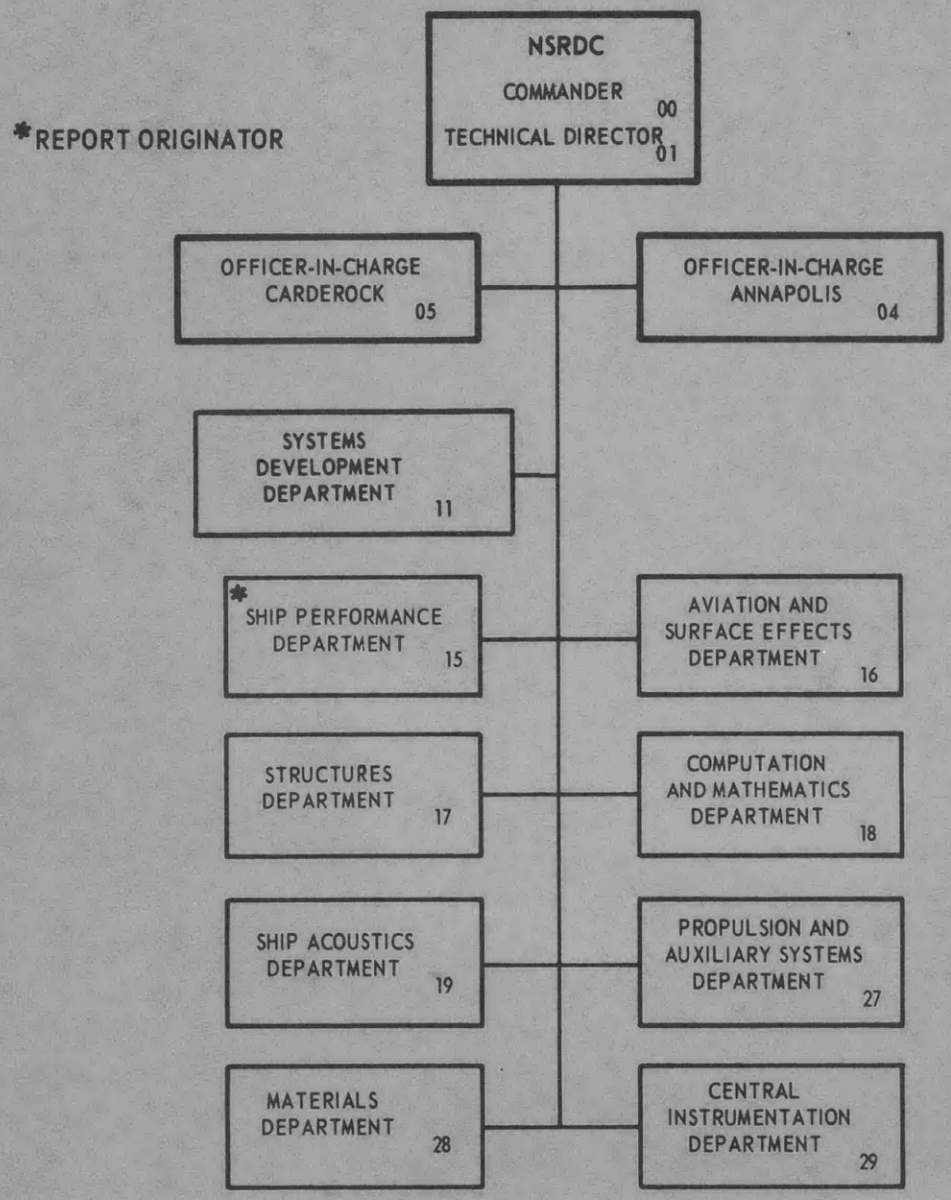

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NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
BETHESDA, MD. 20034

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ABSTRACT

A summary of progress in the achievement of frictional drag reduction is presented in terms of highlights, laboratory activities, and bibliographic entries from the summer of 1971 to the summer of 1972.

ADMINISTRATIVE INFORMATION

The work described in this report was sponsored by the Naval Ordnance Systems Command (Code 035B) and was funded under UR-123-01-03.

INTRODUCTION

The extensive activity underway by many investigators in reducing turbulent skin friction has prompted this annual survey. A brief summary of significant developments is given from a perusal of the literature appearing over the year, summer of 1971 to summer of 1972. A laboratory survey is presented of work in progress. The statements are in response to a letter of inquiry and are repeated almost verbatim. The bibliography lists the published literature discovered by the author over the year.

PROGRESS IN DRAG REDUCTION - SUMMER 1971 TO SUMMER 1972

GENERAL

Activity in drag reduction with polymer additives continues unabated and with great vigor. Note the 153 bibliographical entries since the listing last summer (45).* A symposium was held by the American Institute of Chemical Engineers, May 1972 in St. Louis. See bibliographical entries 25, 139, 132, 152, 109, 135, 134, 41, and 52. This follows the A.I.Ch.E. symposium in January 1970 which has just appeared as a separate publication in the Chemical Engineering Progress Symposium Series as "Drag Reduction" with J. G. Savins and P. S. Virk as editors. (See Entries 140, 51, 82, 71, 118,

*Numbers refer to bibliography on pages 29-43.

90, 95, 12, 70, 8, 153, 31, and 55.) The proceedings of the Drag Reduction workshop held by the Office of Naval Research, Boston Branch Office, in October 1970 has also just been published with A. D. Wood (145) as Technical Coordinator (86, 131, 92, 54, 44, 122, 65, 58, 149, 80, 121, 106, 142, 21, and 59).

Three state-of-the-art summaries have also appeared. Hoyt in the role of a Freeman scholar (American Society of Mechanical Engineers) presents a comprehensive summary (61). Gadd has written a summary of drag reduction for the Encyclopedia of Polymer Science (34). Darby (17) summarizes and evaluates current theories on the mechanism of drag reduction.

FUNDAMENTAL ASPECTS

The part that the elasticity of the polymer molecule plays in drag reduction seems inconsequential when it is observed that rigid particles also exhibit drag reduction. Tests with rigid solid particles suspended in air (114) or water (105) demonstrate this. Rodlike particles show drag reduction (74) while spherical particles do not.

Kerekes and Douglas (74) relate the viscosity properties of fiber suspensions to the drag reduction. Rigid nylon fibers of length-to-diameter ratio 12 to 74 and lengths 1/2 to 2 mm were investigated. Viscous properties of suspensions are divided into three classes depending on the concentration:

I. At low particle concentrations, the suspending fluid is disturbed by the presence of individual particles. Particle behavior is governed by viscous forces and the suspension viscosity is the summation of the fluid viscosity and the particulate effect. The influence of inter-particle collision is small.

II. At intermediate particle concentrations, hydrodynamic perturbations increase due to a substantial number of multi-particle collisions. Particle inertial forces become appreciable in comparison with viscous forces.

III. At large particle concentrations, the particles are so inhibited in motion that the structural effect resulting from inter-particle contact predominates over fluid dynamical behavior. Under these conditions, the suspension tends to exhibit distinctly non-Newtonian properties such as a yield stress.

The limits of Class II are given quantitatively by

$$\frac{1.5}{r^2} \lesssim C \lesssim \frac{0.18\ (3\ell n2r - 1.80)}{r}$$

where C is the concentration and r the length-to-diameter ratio.

It is found that experimentally Class II shows the most drag reduction.

The conclusion is that for drag reduction the influence of the solid particles in reducing the momentum transfer of the fluid along the pipe radius by retarding the inertial eddies must be greater than the opposing effect of increasing the momentum transfer by inter-particle contact. It is further concluded that the drag-reduction mechanism should be based on a non-elastic and non-continum medium in which the visco-inertial action of the particles interacts with the surrounding fluid. The radial motions of the inertial-scale eddies near the wall are retarded.

Experimental evidence (99) from manipulating chemically the shape of polymer molecules shows that a rod-like structure is desirable for drag reduction.

Extensive experimental work continues on the flow close to the wall where the laminar sublayer displays an unsteady behavior in order to elucidate the drag-reduction mechanism (15, 7, 30, 31, 32, 117, 91, and 93).

An increase in particle concentration near the wall due to particle-wall interaction is postulated (110).

Measurements (143) of the velocity distribution for a complex soap system also show the interactive logarithmic law previously found for polymer solutions.

In studies of pulsed flow (135), it is found that the residency time of fluid elements is increased near the wall which results in a lesser momentum exchange and hence a lower skin friction.

CORRELATION

Analytical relations are derived (47) for the resisting moment of a rotating disk in drag-reducing polymer solutions with smooth or rough

surfaces. Relations are available for determining ΔB-correlations for tests with arbitrary surface roughness and/or drag-reducing solutions. Then drag reductions can be predicted for other bodies. The rotating disk allows the attainment of high shearing stresses under laboratory conditions.

DIFFUSION AND INJECTION

The diffusion of polymer molecules into a turbulent shear layer has been experimentally found to be less than that for soluble containments (130, 146, and 147). This is to be expected owing to the diminished momentum transfer.

Poreh and Hsu (108) develop analytical relations for the ejection from a point (line) source. Experimental studies by Wu and Tulin (150) for injection from a slot indicate the following conclusions:

1. Slot injection angle should be small.
2. Slot width should be comparable to the thickness of the viscous sublayer.
3. The most economical injection rate should be close to the flow in the viscous sublayer.

In the case of distributed injection, Walters and Wells (141) find that the reduced diffusion of polymer solution has to be included in the analysis. Furthermore, the polymer solution is only effective in the interactive sublayer (which is to be expected).

DEGRADATION

The susceptibility of polymer molecules to mechanical degradation and the usual lessening of drag reduction is important to practical application in many cases. High shear rate is considered to be a prime factor in promoting degradation. It might be that it is not the shear rate per se but the associated turbulent buffeting that causes degradation. To test this Barnard and Sellin (5) subjected a polymer solution to an intense shear rate in a completely laminar flow. There was degradation as shown by a lessened drag reduction due to smaller molecules when the solution was tested in a turbulent flow.

Kenis (73) experimentally evaluated the comparative susceptibility of polymer molecules to degradation and found Polyox > polyacrylamide > bacterial polysaccharide (Xanthomous campestris) > Guar gum. This confirms current thinking. Fisher and Rodriguez (22) also found Polyox more susceptible than polyacrylamide.

Additional studies on degradation are reported by Ellis and Ting (21), Wade and Kumar (138), Sylvester and Kumar (132), and Huang and Santelli (66).

APPLICATIONS

Drag reduction studies in open channels by Sellin and Barnard (126) may be applied to hydraulic problems like coping with peak discharges during flooding of waterways.

Fabula (23) discusses the application of polymers to fire fighting.

Wade (139) in studies of the ecological implications in the use of Polyox or polyacrylamides shows there is no need for concern. Both are readily degradable by chemical or biological means.

Greskovich and Shrier (50) show that polymers also provide drag reduction in two-phase systems such as gas-liquid systems.

Medical applications for improving blood flow are being developed in (14), (48), (49), and (135).

SUMMARY OF DRAG-REDUCTION RESEARCH IN LABORATORIES - 1972

DEFINITIONS

1. Title of Project
    a. Principal Investigators
    b. Description of Project
    c. Results
    d. Publications

UNIVERSITY OF AKRON
Department of Chemical Engineering
Akron, Ohio 44303

1. Biomedical Implications of Drag Reducing Agents
    a. H. L. Greene, R. F. Nokes, and L. C. Thomas

b. Research is being undertaken to determine both hydrodynamic and biological effects of soluble polymeric substances (drag-reducing agents) on blood flow. Existence of turbulence within the vascular system suggests that more efficient pumping of blood may be possible when minute quantities of these agents are added.

c. Results have shown that pressure drop in turbulent blood flow (*in vitro*) is substantially reduced by polymer addition. *In vivo* experiments will hopefully substantiate this. Toxicity of typical drag-reducing polymer appears minimal. Turbulence intensity and renewal frequencies as obtained by hot film anemometer data have been found to be substantially decreased. Other effects of fluid viscoelasticity on vascular flows are also being investigated.

d. (48) (49) (135)

Greene, H. L., R. F. Nokes, and L. C. Thomas, "Biomedical Implications of Drag Reducing Agents," Biorheology, in press, 1971.

Nokes, R. F., H. L. Greene, and L. C. Thomas, "Ventricular Myograph Tracing During Polyacrylamide Perfusion," 24th Annual Conference on Engineering in Medicine and Biology, 1971.

ARIZONA STATE UNIVERSITY
College of Engineering Sciences
Tempe, Arizona 95281

1. Laser Doppler Studies on Dilute Polymer Solutions

a. Neil S. Berman

b. Measurements in time dependent flows using a laser doppler velocimeter are continuing. At present, some fundamental questions regarding the interpretation of frequency spectra are under study.

c. and d. (7)

UNIVERSITY OF BRISTOL
Department of Civil Engineering
Bristol, England

1. Drag-Reducing Polymer Additives in Storm Water Sewers

a. R. H. J. Sellin

b. An investigation into the possible use of drag reducing polymers to increase the capacity of storm sewers during peak flow periods. Early full-scale experiments have given encouraging results but point the need for carefully instrumented experiments under as wide a range as possible of sewer sizes and discharge quantities. A programme of tests is being planned with the cooperation of the Bristol City Engineer's Department and the

assistance of the Hydraulics Research Station, Wallingford, England. The work is sponsored by a grant from the U. K. government, Department of the Environment.

c. Results have been obtained from tests in 12- and 36-in. diameter sewers. The best results show an increase in velocity under steady hydraulic pressure gradient of 29%. The effect of pipe size and surface condition is thought to be critical and more studies are planned to clarify these factors. Auxiliary studies include the development of an automatic and reliable polymer powder dosing plant.

d. (126) (127)

2. Degradation of Aqueous Solutions of Polyox WSR-301 under Both Laminar and Turbulent Shear Stresses

a. R. H. J. Sellin and B. J. S. Barnard

b. Polymer solutions of drag-reducing concentration were submitted to shear stress in two separate flow situations:

(1) In a dashpot apparatus where the fluid was forced to escape through the annular gap between piston and cylinder wall under laminar flow conditions

(2) Under turbulent pipe flow in a 1 mm bore tube, Reynolds number 15,000, in which the wall shear stress was of the same order as that calculated for (1) above.

c. The polymer solutions sheared in the methods described above were tested in a pipe flow apparatus which measured the remaining drag-reducing capability of the solution and hence the degradation suffered. After making certain assumptions about the proportion of the sample passing through the region of high shear stress (close to the walls) in the dashpot experiment, comparisons based on a total time under shear between the two degradation rates showed a measure of agreement. This suggests that the high shear rates found in the laminar flow region close to the wall in turbulent pipe flow play a significant part in degrading drag-reducing dilute polymer solutions.

CLEMSON UNIVERSITY
Department of Engineering Mechanics
Clemson, South Carolina 29631

1. The Effect of Polymer Additives on Dispersion in Pipe Flow

a. Walter E. Castro, Paul B. Zielinski, and William McCabe

b. The objective of this investigation is to determine the effect of polymer additives on longitudinal dispersion in a pipe. Small conductivity measuring probes are mounted in the pipe at stations 8 and 29.5 ft from a slug injection block. The procedure used in this investigation is to inject a slug of polymer into a water flow or a slug of salt into a polymer flow, and measure the continuous changes in conductivity as the polymer

passes through the two test stations. From these time-concentration curves, the dispersion which occurs between the two test stations is computed.

c. Our work so far indicates that polymer additives will greatly increase dispersion where there is noticable reduction in drag coefficient. The increase in dispersion is found to be directly related to the degree of drag reduction. Thus, when the polymer additives become ineffective as drag reducers, they also become ineffective as dispersion enhancers.

2. Drug Reduction in Prosthetic Heart Valves Using High Polymer Additives

a. Walter E. Castro, B. W. Sauer, and R. Larry Dooley

b. The objective here is to determine the effectiveness of high polymer additives in reducing turbulent drag associated with prosthetic heart valves. An extensive *in vitro* study is currently being conducted. Different prosthetic valves are being tested using a constant head tank and machined acrylic heart valve test chamber.

Different additives are being investigated for their effectiveness in reducing the pressure drop overall across the valve and for their effectiveness in reducing wall pressure fluctuations in the wake flow.

c. Results: Preliminary data using tap water indicates significant drag reduction using high polymer additives. Research presently in progress using blood and analog solutions, with and without additives, indicates equally significant drag reduction. One high polymer that shows extreme promise as a drag reducing additive in blood flow is okra mucilage--a natural polysaccharide.

Toxicologic studies are currently being conducted on some of the more promising materials.

d. (14)

Castro, W. E., R. L. Dooley, and B. W. Sauer, "Drag Reduction in Prosthetic Heart Valves Using High Polymer Additives," paper submitted for presentation at the 25th American Conference for Engineering in Medicine and Biology.

3. The Effect of Drag Reducing Additives on Turbulent Dispersion

a. Walter E. Castro, Paul B. Zielinski, and Jerald P. Peterson

b. The objective of the project is to determine the effect of polymer drag-reducing additives on the virtual turbulent dispersion coefficient. The effect is being studied both theoretically and experimentally. The experimental work is being done in a two-dimensional flow field in a laboratory flume. Tracer concentration profiles in the longitudinal direction are measured at stations along the length of the flume using electrical conductivity probes. Correlation of the data will be attempted by determining the dependence of the turbulent dispersion coefficient on polymer concentration.

c. Both theoretical and experimental results indicate a large increase in the longitudinal turbulent dispersion coefficient in the presence of drag reducing additives for drag reducing flows.

d. In preparation.

COLORADO STATE UNIVERSITY
Department of Civil Engineering
Fort Collins, Colorado 80521

1. Viscous Drag Reduction for Polymer Injection into Developing Boundary Layers

a. J. P. Tullis

b. The project involved polymer injection into a developing boundary layer in a pipe. Wall shear stress, boundary layer development, velocity profile, turbulence and diffusion are being investigated. The facility consists of a 12-in. diameter pipe, 200 ft long with a 5-ft diameter settling chamber and converging nozzle. Polymer is injected at rates up to 200 gallons per min through rows of 3/8-in. diameter holes drilled at 30 deg to the pipe. Data are being collected at Reynolds numbers between 3×10^5 and 3×10^6.

c. The work completed to date includes the following:

(1) A thorough study of the inlet region without polymer injection. Development of wall shear stress, growth of the turbulent boundary layer, core velocity, velocity profile and pressure coefficients were evaluated. An analytical model was developed to predict the growth of the boundary layer, core velocity and pressure coefficients. Good agreement between the model and experimental results was found for the first 12 pipe diameters.

(2) Viscous drag reduction was studied for injection concentrations between 100 and 2400 ppm. Near the injector, higher drag reduction was obtained with lower injection concentrations. Further downstream the drag reduction was independent of injection concentration. The injector was evaluated to determine the effect of injection velocity and the existence of any degradation caused by the injector. Drag reductions in access of 90 percent were found in the inlet region. Degradation was observed for all conditions at Reynolds numbers greater than 10^6. The data suggest that in fully rough pipe flow, drag reduction will not exist. Velocity profile measurements indicate that with polymer injection the boundary layer grows much slower, the velocity profile is much fuller and requires a much greater distance to become fully developed. Current work includes development of a model for predicting boundary layer growth with polymer injection, and collecting experimental data for its verification, measurements of turbulent diffusion of the polymer, and turbulent measurements.

d. Wang, Jeng-Song, "Turbulent Flow in a Pipe Inlet Region," Ph.D. dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, June 1972.

Lindeman, L. F., "Polymer Injection for Drag Reduction," M.S. thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, June 1972.

CORNELL UNIVERSITY
School of Chemical Engineering
Ithaca, New York 14850

1. Degradation of Drag-Reducing Polymers

a. F. Rodriguez

b. Studies of drag reduction in aqueous and non-aqueous solvents. Polymers include poly(ethylene oxide), polyacrylamide, polystyrene, and aluminum di-2-ethylhexoate. Primary emphasis is on effects of molecular weight and solvent character on effectiveness of drag reduction and on polymer degradation during drag reduction.

c. Time-concentration superposition has been demonstrated in some experiments.

d. (28), (109), (111)

GEORGIA INSTITUTE OF TECHNOLOGY
School of Civil Engineering
Atlanta, Georgia 30332

1. Unsteady Flow of Dilute Aqueous Polymer Solutions in Pipe Networks--A Method to Improve Water Distribution

a. Paul G. Mayer

b. Laboratory experiments with unsteady polymer flow in a single pipe. Numerical modelling of unsteady flow through pipe networks.

c. Laboratory work was correlated by a numerical model for a simple pipe. No experimental verification for the unsteady flow in a pipe network is presently available.

HENDON COLLEGE OF TECHNOLOGY
Department of Mechanical Engineering
London NW4, England

1. Flow Characteristics of Solutions and Suspensions with Drag-Reducing Additives.

a. A. White

b. Characteristics of boundary layers and pipe flows with drag-reducing additives are being studied using the hydrogen bubble technique for flow visualization and laser doppler anemometer.

c. and d. (143).

UNIVERSITY OF ILLINOIS
Department of Chemical Engineering
Urbana, Illinois 61801

1. Effect of Drag-Reducing Polymers on Turbulence Structure

a. Thomas J. Hanratty and George McConaghy

b. Electrochemical wall mass transfer probes are being used to study the influence of drag-reducing polymers on turbulence in the viscous sublayer.

c. The principal effect is to increase the wave length of flow oriented eddies. An important secondary effect is the decrease in the intensity of the transverse velocity fluctuations.

d. (19), (32)

UNIVERSITY OF IOWA
Institute of Hydraulic Research
Iowa City, Iowa 52240

1. Frictional Resistance of Flat Plates in Dilute Polymer Solutions

a. L. Landweber and M. Poreh

b. A one-parameter family of inner-law velocity profiles, derived from the mixing-length hypothesis, and similarity laws from flows of dilute polymer solutions in pipes are combined with an assumption concerning polymer effectiveness when ranges of the inner and outer boundary-layer laws do not overlap to predict boundary layer characteristics.

c. Analytical expressions for velocity profiles, shear stress and total frictional resistance, as functions of polymer type and concentration, are derived, and results are presented in tables and figures. Results show a maximum-drag-reduction curve.

ISRAEL INSTITUTE OF TECHNOLOGY
Department of Civil Engineering
Haifa, Israel

1. Turbulent Flow of Drag Reducing Polymers

a. M. Poreh

b. Basic study of the phenomenon

c. A model with a single, variable-damping parameter is used to describe flow of drag reducing polymers. The model seems to be in better agreement with the data than the elastic sublayer model of Virk.

d. Poreh, M. and Y. Dimant, "Velocity Distribution in Flows with Drag Reduction," Preprints, Proceedings of the 9th Naval Hydrodynamics Symposium, 19 August 1972.

UNIVERSITÉ LOUIS PASTEUR DE STRASBOURG
Institue of Fluid Mechanics
Strasbourg, France

1. Studies of non-Newtonian Hydrodynamic Boundary Layers

a. L. A. Sackmann, C. Gebel, J. L. Eichhorn, H. Reitzer, and O. Scrivener

b. (1) Internal flow - Study of head losses and velocity profiles of pipe flows with wall and inside injections of non-Newtonian fluids.

(2) External flow - Study of velocity fields and pressures of bodies in a water tunnel with wall injections of non-Newtonian fluids. Study of resulting drag.

(3) Special flows - Study of flow around particles in suspension in a rising jet.

c. (1) Internal flow - Marked reduction in head loss (60 percent) which is a function of Reynolds number, concentration and type of non-Newtonian fluid. Less reduction with wall injection. Critical Reynolds number for onset of reduction. Flattening of velocity profile and reduction of velocity in viscous sublayer.

(2) External flow - Modification of velocity field on bodies with wall injection at stagnation point: velocity increase in turbulent boundary layer.

Pressure distribution: decrease in pressure on nose and increase in wake; downstream movement of separation.

Drag reduction of flat plate (72 percent).

The critical velocity for onset of drag reduction for an unsteady body in non-Newtonian fluid depends on the acceleration. At start of motion, there exists a critical time for the appearance of drag reduction.

(3) Special flows - Experimental determination of law relating flow velocity to the void space of a mass of particles in suspension.

Rheology - Determination of conditions for preparing and preserving aqueous solutions of the macromolecules. Determination of rheograms and their dependence on concentration and temperature.

d. (120), (124), (125), (128), (37)

"Hydrodynamique des lits fluidisés," M. Gebel, C.E.D.O.C.A.R., juillet, 1971.

"Cinétique et dynamique des lits fluidisés," M. Gebel, C.E.D.O.C.A.R. (microfiches), September 1971.

"Correlation entre la vitesse moyenne de debit et la fraction de vide d'un lit fluidisés," M. Gebel, H. Reitzer, J. L. Eichhorn, C.R.A.S., 17.4, 1972.

Compte-rendu des XIIèmes Journées de l'Hydraulique, juin 1972.

"Ecoulement externe ou interne de solutions de corps macromoléculaires," M. Gebel, H. Reitzer, O. Scrivener.

Congrès International de Rhéologie, Lyon, September 1972.

McMASTER UNIVERSITY
Department of Mechanical Engineering
Hamilton, Ontario, Canada

1. Diffusion of High Polymers in External Boundary Layer Flows

a. Brian Latto

b. Measurements of the diffusion rates of high polymers injected into the turbulent boundary layer formed on a flat plate are being made. Measurements with free-stream flow rates up to five ft per sec are being made to ascertain the relationship between injection rate, concentration level, and free-stream velocity and tubulence, on the diffusion of drag reducing polymers in external two-dimensional flows. Results have been obtained and are presently being analyzed, but tentatively indicate much lower tubulent diffusion rates than for a pure fluid injection flow.

2. Measurements of the Drag-Reducing Effectiveness of High Polymers in External Boundary Layer Flows

a. Brian Latto

b. An 8-ft long flat plate is being used to measure the drag reduction effectiveness of high polymers injected into two-dimensional turbulent boundary layers. A floating test section suspended on springs is being used to measure drag. Free-stream velocities of up to four ft per sec are being used with Reynolds numbers of the order of ten to the sixth. This work is a continuation of previous work on the matter but incorporates a much improved apparatus with much more stability.

3. Effect of Drag Reducing Polymers on the Movement of Spheres and Other Bodies in Pipeline Transportation

a. Brian Latto and George F. Round

b. A two-in. diameter pipeline approximately 40-ft long located in vertical plane is being used to measure the drag on freely suspended spheres in homogeneous dilute polymer solution flows. Relationships between the diameter of the sphere to the diameter of the pipeline ratio, the free-stream velocity and density ratio between the sphere and the fluid are being obtained. Furthermore, the effectiveness of polymer additives on sphere and other body trains is also being investigated. Results have been obtained but are not as yet available for publication.

4. Effects of High Polymers on the Performance of Hydraulic Pumps

a. Brian Latto

b. The effects of high polymer additives on the performance of centrifugal and other types of water pumps are being investigated. Data on pump efficiency and head as well as degradation of the solution are being obtained and indicate some unusual results at certain flow conditions. Polyhall and Reten type polymers are being used at present. A McMaster report is available.

MESSERSCHMITT-BÖLKOW-BLOHM GMBH.
8 München 80
Germany

1. Method for Continuously Injecting Drag-Reducing Fluid into a Boundary Layer

a. F. P. Kilian

2. Effect of Visoelastic Polymers on Propellers

a. F. P. Kilian

d. (76)

3. Development of Theory for Turbulent Flow of Drag-Reducing Fluids

a. F. P. Kilian

d. (75)

UNIVERSITY OF MICHIGAN
Department of Engineering Mechanics
Ann Arbor, Michigan 48104

1. Drag Reduction

a. W. P. Graebel

b. An experimental investigation of pipe flow of fluids with drag-reducing polymer additives. A two-component laser-doppler anemometer is utilized in measuring mean and turbulent velocity components. Also, theoretical studies of the stability of flows are being conducted using asymptotic and invariant imbedding techniques.

c. Results so far have been in obtaining one-component measurements using a laser-doppler anemometer.

d. (15)

Curl, M. L. and W. P. Graebel, "Application of Invariant Imbedding Techniques to Flow Stability Problems," to appear in SIAM, Journal of Applied Math.

UNIVERSITY OF MINNESOTA
St. Anthony Falls Hydraulic Laboratory
Minneapolis, Minnesota 55414

1. The Effect of Drag-Reducing Polymer on Surface Pressure Fluctuation on Rough Surfaces

a. J. M. Killen and J. M. Wetzel

b. A preliminary investigation of shear fluctuations as influenced by polymer additives.

c. Characteristics of a flush-mounted hot-film sensor were investigated in turbulent flows of both water and drag-reducing polymer solutions in a 4-in. diameter pipe. For water flows, a linear relationship was found between the average power supplied to the sensor and the cube root of the wall shear stress. With the addition of polymer additives, the heat transfer rates at a given shear stress were reduced from those found with water alone. Further analysis of the fluctuations of heat transfer obtained in various flow facilities has shown that the zero-crossing rate is related to the wall shear stress and to fluid properties for water, polymer, and also for air flows. The zero-crossing rate was not dependent on sensor sensitivity or contamination. Evaluations of the microscale indicated that it had increased following the addition of the drag-reducing polymer to the water. Autocorrelations were made with the heat transfer fluctuations, but attempts to obtain cross-correlation coefficients between heat transfer and surface pressure fluctuations as measured with a small hydrophone were unsuccessful. The limited data for the autocorrelation were not conclusive. The zero-crossing rate of the surface pressure fluctuations was related to the local wall shear stress.

d. Wetzel, J. M. and J. M. Killen, "A Preliminary Report on the Zero Crossing Technique for Shear Measurements," Project Report 134, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, April 1972.

UNIVERSITY OF MISSOURI - ROLLA
Department of Chemical Engineering
Rolla, Missouri 65401

1. Drag Reduction in Hydrocarbon Soap Solutions

a. J. L. Zakin

b. The effects of concentration, aging, shear stress and the presence of peptizers on drag reduction of hydrocarbon solutions of aluminum soaps.

c. At low concentrations, these systems showed an upper critical shear stress above which drag reduction was gradually lost. Degradation of the soap micelle structure occurred relatively rapidly above this point and recovery was slow. The effect of peptizers is complex. In some situations, it enhanced and in other cases reduced the drag-reducing ability of the soap polymers.

d. (151), (152)

2. Drag Reduction in Aqueous Detergent Systems

a. J. L. Zakin

b. The effects of concentration, aging, shear stress, and salt concentration on drag reduction of aqueous detergent solutions are being studied.

3. Drag Reduction in Solid-Liquid Flow

a. J. L. Zakin and G. K. Patterson

b. The effects of particle size, shape, and concentration on drag reduction in solid liquid flows are being studied.

4. Mechanical Degradation of Dilute Polymer

a. J. L. Zakin, G. K. Patterson, and J. Culter

b. The effect of concentration, molecular weight, shear stress, polymer type, and solvent on the rate of degradation of dilute polymer solutions and the effect of degradation on drag reduction are being studied.

5. Measurement of Solution Complex Viscosities at High Shear Strains

a. G. K. Patterson

b. An instrument has been developed which successfully measures η' and η'' in the audiofrequency range (30-1500 cps) at strain amplitudes beyond the linear range. Improvements are being sought to increase sensitivity to lower the viscosity limit from 50 to approximately 5 centipoise.

d. Shen, K.-S., "Measurement of Complex Viscosity in Solutions at Finite Shear Strains," Ph.D. Thesis, University of Missouri - Rolla, 1971.

6. Drag Reduction by Polymers in Hydrocarbon Systems

a. J. L. Zakin and G. K. Patterson

b. The effects of molecular variables on polymer drag reduction and turbulence structure are being studied.

c. Turbulence intensities and frequency spectra vary in a complex but repeatable manner which can be explained in terms of a two-Deborah number model.

d. "Turbulence Measurements in Drag-Reducing Flow," J. M. Rodriguez, G. K. Patterson, and J. L. Zakin, Proceedings Symposium on Fluid Dynamics, McMaster University, Canada, in press.

NAVAL POSTGRADUATE SCHOOL
Department of Mechanical Engineering
Monterey, California 93940

1. Flow of Polymer Solutions about Cylinders and Hydrofoils

a. T. Sarpkaya

b. Flow of the aqueous solutions of Polyox WSR-301, with concentrations of 1 ppm to 100 ppm, and of the pure solvent (tap and distilled water) about circular cylinders and hydrofoils has been investigated through the use of a water tunnel. Direct and pressure integrated drag coefficients, pressure distribution, frequency spectrum, turbulence distribution, etc., were determined for flows of solutions at all levels of degradation and compared with the reference measurements made in pure-solvent flows.

c. During the course of the investigation, a critically degraded solution was observed to cause, at a particular Reynolds number, an unforeseen instability in the boundary layer and in all the other flow characteristics. This instability which most easily manifested itself in the form of an abrupt drag-force jump from a high subcritical value to a low supercritical value, became one of the central issues of the investigation. The observations, measurements, and the comparisons made suggest that polymer adsorption on to the test bodies and the development of inflexional-velocity profiles (primarily because of and within the partly adsorbed partly transported layer) are responsible for the observed instability, the downstream shift of the separation point, and the lowering of the transition Reynolds numbers. A comprehensive review of the pertinent literature has also been made.

d. (123)

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Sarpkaya, T., P. G. Rainey, and R. E. Kell, "Flow of Dilute Polymer (Polyox WSR-301) Solutions About Circular Cylinders," to appear in the Journal of Fluid Mechanics.

Department of Physics

1. Polymers and Propellers

a. J. V. Sanders

b. Thrust and torque were measured and efficiency calculated for a 14.6-cm diameter, two-bladed propeller in aqueous solutions or Polyethylene oxide, WSR-301, with concentrations ranging from 0 to 75 wppm*. Acoustic measurements were also made.

c. For the propeller operating under heavily-loaded conditions, the thrust decreased with increasing concentration while the torque passed through a minimum at 100 wppm. The net result was that the propeller efficiency remained essentially constant except for a small increase of a few percent at 10 wppm. The polymer greatly reduced the rate of propeller cavitation but did not influence the rotational speed at which cavitation was first noticed.

d. Henderson, L., "Effects of Polyethylene-oxide Solutions on the Performance of a Small Propeller," M.S. Thesis, Naval Postgraduate School, Monterey, California, 93940 (September 1971).

White, R., "Propeller Cavitation in Solutions of Polyethylene Oxide," M.S. Thesis, Naval Postgraduate School, Monterey, California, 93940 (December 1971).

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NAVAL RESEARCH LABORATORY
Surface Chemistry Branch
Washington, D. C. 20390

1. Drag Reduction

a. R. C. Little, R. Y. Ting, O. Kim, and D. Hunston

b. New classes of drag-reducing additives are being synthesized by varying both the polymer structure and the characteristic lengths of substituted polymer chains. Drag reduction effectiveness, shear stability and other desirable solution properties are being studied.

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*wppm = weight parts per million

c. (1) A series of acrylamide and acrylic acids homopolymers covering molecular weights ranging from 1.5×10^6 to 6.7×10^6 were synthesized. A polyacrylamide sample was successfully modified in two ways: (a) by hydrolysis to yield three derivatives having different degrees of hydrolysis, and (b) by modification with glyoxal to introduce bulky side groups to the linear main chain. The drag reduction properties of these samples were characterized in a turbulent pipe flow apparatus. The experimental results indicated that drag reduction was improved when the modifications introduced a larger molecular length scale.

(2) By applying a constitutive equation based on a modified dumbbell model, two proposed mechanisms responsible for drag reduction of dilute polymer solutions in turbulent flow were examined. An analysis for the case of oscillatory shearing showed that the viscoelastic effect on the mean local rate of energy dissipation of a fluid element oscillating sinusoidally was negligibly small. The results of analyzing an elongational flow indicated that the elongational viscosity in a viscoelastic fluid may increase to very large values as the stretching rate and the time exceed certain limiting values. It is therefore concluded that turbulent drag reduction may result from turbulent suppression by high elongational viscosity effects involved in the turbulent bursting process in turbulent boundary layers. These results also support the concept that the time scale ratio is the more important and relevant factor in the drag-reduction effect.

d. (29), (103), (53), (55), (83), (84), (85)

Ting, R. Y. and O. K. Kim, "Drag Reduction Properties of Ultra-High Molecular Weight Polyacrylamide and Related Polymers," presented at American Chemical Society Meeting, August 1972, New York, N. Y.

Hansen, R. J., R. C. Little, and P. C. Forame, "Experimental and Theoretical Studies of Early Turbulence," to be presented at the 1st Pacific Congress on Chemical Engineering, Kyoto, Japan, October 1972.

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Ship Performance Department
Bethesda, Maryland 20034

1. Drag Reduction and Shear Degradation of Dilute Polymer Solutions as Measured by a Rotating Disk

a. T. T. Huang and N. Santelli

b. and c.

Drag reduction measured by a rotating disk is found to have three domains; oversaturated, optimal, and undersaturated. At a given boundary layer thickness and wall shear stress, the drag reduction increases with increasing concentration in the undersaturated domain and the drag reduction does not increase with increasing concentration in the oversaturated domain. The boundary between the two domains is the optimal drag reduction which is

determined by the type of polymer and its concentration and a Reynolds number, $u_\tau R/\nu$ or $u_\tau \delta/\nu$, based on shear velocity and disk radius or boundary layer thickness. Each drag-reduction domain has its distinct shear degradation characteristic. The measured shear degradation for a given polymer solution in optimal and undersaturated domains is found to depend upon the concentration, the specific energy dissipation, wall shear stress, and the ambient temperature of the solvent. However, the polymer solution in the oversaturated domain may not show any degradation in drag reduction if the specific energy dissipated by the solution is not sufficiently large.

d. NSRDC Report 3678 (in press).

2. The Torque and Turbulent Boundary Layer of Rotating Disks with Smooth and Rough Surfaces, and in Drag-Reducing Polymer Solutions

a. P. S. Granville

b. The principal aim is to develop analytical relations between the resisting torque coefficient and the disk Reynolds numbers for the case of roughness and/or polymer additives in terms of boundary-layer factors. The relations between magnitude and direction of local skin friction (wall shearing stress) and Reynolds number also result. The basis of the analysis is the similarity-law correlation for roughness and/or polymer additives. If the empirical factors in the similarity-law correlation are known, the torque and other properties of the flow may be predicted. Conversely, if the torque coefficient and Reynolds number are measured, the similarity-law empirical factors may be deduced. This is a most valuable attribute since the rotating disk may then be used as an instrument for experimentally obtaining similarity-law correlations for various types of irregular roughnesses and/or polymer additives at high shearing stresses. Once a similarity-law correlation is known, it may be used to predict the characteristics of other types of shear flows.

c. A general logarithmic formula is derived for the resisting moment of rotating disks which applies to arbitrary rough surfaces and/or drag-reducing polymer solutions. The special cases considered include:

(1) Smooth surfaces.
(2) Fully rough surfaces.
(3) Polymer solutions with a linear logarithmic drag-reduction characterization.
(4) Maximum drag reduction with polymer solution.

Formulas are also derived for the local skin friction, the boundary-layer thickness, the displacement thickness, and the momentum thickness as functions of Reynolds number. In addition, solutions are obtained for the skewness of the boundary-layer velocity and for the skewness of the wall shearing stress.

d. (47)

Propulsion and Auxiliary Systems Department
Annapolis, Maryland

1. Pump and Pipe System Characteristics with Dilute Drag-Reducing Solutions

a. George F. Wilhelmi

b. Investigation to determine degradation and hydrodynamic effects of dilute drag-reducing solutions flowing through a centrifugal pump in a full-scale experimental system has been completed.

c. Results of this investigation show that the centrifugal pump operating characteristics with dilute solutions of drag-reducing agent deviated only to a small extent from freshwater performance. Mechanical degradation of the drag-reducing agent as it flowed through the pump was shown to be a function of solution concentration and flow rate. Degradation varied from complete loss of effectiveness at low flow rates to relatively small changes at higher capacities near the best efficiency point. Performance of the drag-reducing agent in a 2 1/2-in. piping system has been characterized in fully-developed turbulent flow.

NAVAL UNDERSEA CENTER
Pasadena Laboratory
Pasadena, California 91107

1. Drag Reduction Molecular Study

a. Robert H. Wade

b. The concept of drag reduction by polymer additives has been well-established. The selection of the polymeric materials for drag reduction has, however, been largely empirical. This project is directed toward a better understanding of the relationships between several polymer parameters and drag reduction effectiveness, and should allow eventual synthesis of better drag-reducing additives. Work is underway to obtain and synthesize polymeric materials having a wide variation in the chemical and physical parameters expected to cause a significant change in drag reduction effectiveness. The main parameters selected for study are: the nature of the repeating unit, the degree of polymerization, molecular shape and flexibility, chain branching, ionization, cross-linking, degradation susceptibility and pollution potential.

c. The effect of varying numbers and lengths of side chains on the drag-reduction effectiveness and degradation susceptibility of a constant length backbone polymer is being investigated. A reaction to graft side chains on polyvinyl alcohol, without the interference of homopolymer formation, has been developed. Polyvinyl alcohol, of sufficiently high molecular weight to exhibit drag reduction was prepared (it is believed, for the first time) by low temperature polymerization of vinyl acetate. Samples of varying degrees of acrylamide branching have been prepared and are under evaluation.

The reaction of non-drag reducing polyvinyl alcohol with dialdehydes has produced cross-linked polymers showing drag reduction capability. The time of reaction is critical. Drag reduction reaches a maximum at a time dependent on reaction conditions and decreases to zero, indicating a molecule of increased size but of limited cross-link density to be most efficient. Reactions with larger polyvinyl alcohol are underway.

The pollution potential of poly(ethylene oxide) and polyacrylamide has been carefully examined and the materials found safe for use.

d. (139)

2. Drag Reduction by Fiber Suspensions

a. J. W. Hoyt

b. and c.

The friction-reducing properties of fiber suspensions were investigated. Fibers of asbestos, glass, and acrylic were found to greatly reduce the turbulent-flow resistance of both aqueous and non-aqueous suspending fluids. Pipe-flow and rotating-disk experiments show that fibers having the smallest diameter, and substantial length-to-diameter ratio gave the most friction reduction at the smallest weight concentration of fiber. An asbestos fiber gave 65 percent friction reduction in a small pipe-flow apparatus and 48 percent in the rotating-disk equipment (both being the maximum obtainable in the devices) at a suspension concentration of 500 ppm.

d. (63), (64)

3. Mechanism of Drag Reduction by Polymer Additives

a. Michael C. Kohn

b. Drag reduction onset constants for six polymer-solvent systems were calculated according to the theories of corresponding length scales (Virk), corresponding time scales (Elata and Zakin), and the rate of energy storage (Walsh).

Molecular parameters were estimated by a least squares fit of the theoretically calculated to observed intrinsic viscosities for several polymer-solvent systems.

The strain energy density of five polymer-solvent systems were estimated using the equation for energy storage derived by Blatz for the case of ideally flexible coils. The eigenvalues were the non-free draining eigenvalues of Pyun and Fixman.

An equation for energy storage using Cerf's theory for the non-ideally flexible case was derived. This theory includes a parameter for the internal stiffness of the polymer chain, the coefficient of internal viscosity.

c. The Virk, Elata-Zakin, and Walsh theories were found to be incapable of predicting the onset of drag reduction with adequate precision. Standard errors of the onset constants were 1.2-2.0 times their mean values.

A plot of the drag ratio versus the strain energy density (from Blatz's equation) showed one curve for the poly(ethylene oxide) system and another for all the other systems. Since the former polymer is much more flexible than the other polymers studied, this result suggests that the internal viscosity of the polymer coil is an important factor in the ability of a macromolecule to store energy.

Preliminary results using the theory of energy storage by macromolecules with internal viscosity suggest that the amount of strain energy is quite sensitive to the coefficient of internal viscosity.

4. Effect of Polymer Additives on Jet Cavitation

a. J. W. Hoyt

b. The effect of dissolved high polymer materials on cavitation inception was studied in a submerged underwater jet. Cavitation inception was determined using a hydrophone sensitive in the 1/2-20 kHz region. Concentrations of poly(ethylene oxide) WSR-301 from 1/2 to 80 ppm were employed both in the jet and the reservoir into which it discharges.

c. The cavitation inception parameter, σ_i, is reduced markedly by the presence of poly(ethylene oxide); 1/2 ppm being detectable. At 70 to 80 ppm the inception index is only half that of pure water. These results were not markedly influenced by changed turbulence levels upstream of the nozzle; in contrast, the inception index of the plain water jet was increased by increased turbulence ahead of the nozzle. The polymer also reduced the surface tension of test fluid; nevertheless, the inception index was greatly reduced.

d. (60), (62), (59), (20)

NETHERLANDS SHIP MODEL BASIN
Wageningen, The Netherlands

1. Friction Reduction and Degradation of Polymer Solutions; Effect on Cavitation

a. J. H. J. van der Meulen

b. A turbulent-flow rheometer has been used to measure friction reduction and degradation of Polyox WSR-301, guar gum, polyacrylamide and CMC solutions in water. By injecting Polyox WSR-301 from the nose of a cylindrical body, the effect on incipient and desinent cavitation is being studied in a high-speed water tunnel.

c. Mixing of polymers does not ameliorate the friction-reducing ability of the most effective component. Guar gum is less liable to degradation due to higher shear stresses than Polyox WSR-301 and polyacrylamide. To a certain extent, cavitation is suppressed by polymer injection.

d. Paper in preparation.

UNIVERSITY OF NOTRE DAME
Department of Chemical Engineering
Notre Dame, Indiana 46556

1. Drag-Reducing Polymer Solutions

a. N. D. Sylvester (Now at University of Tulsa, Oklahoma)

b. Dilute solution viscosity behavior of various drag-reducing polymer solutions was measured with particular emphasis on the effect of electrolytes.

c. Very unusual effects observed for polyelectrolytes.

d. (133)

2. Degradation of Dilute Polymer Solutions in Turbulent Tube Flow

a. N. D. Sylvester

b. The drag-reduction degradation characteristics of Separan AP30 have been measured under continuous turbulent tube flow.

c. A tentative correlation relating the drag-reduction degradation characteristics of dilute SAP30 solutions to concentration, velocity, and intrinsic viscosity has been developed.

d. (132)

Sylvester, N. D. and S. M. Kumor, "Drag Reduction Degradation of Dilute Polymer Solutions in Turbulent Tube Flow," Project Themis Technical Report, UND-71-6, University of Notre Dame, Nov. 1971.

Sylvester, N. D., "Drag Reduction and Flow Properties of Dilute Macromolecular Solutions," Invited Lecture, Chemical Engineering Division, Argonne National Laboratory.

3. Viscoelastic Effects in the Turbulent Boundary Layer of a Submerged Flat Plate

a. N. D. Sylvester

b. Velocity profiles in the sublayer of the turbulent boundary layer of a submerged flat plate for dilute drag-reducing polymer solutions will be measured.

c. Experiments in progress.

d. None as yet.

OKLAHOMA STATE UNIVERSITY
School of Mechanical and Aerospace Engineering
Stillwater, Oklahoma 74074

1. Visual Studies of the Near-Wall Region in Drag-Reducing Channel Flows

a. W. G. Tiederman

b. Wall slot dye injection and hydrogen bubble tracers are being used to determine the effect of a dilute polymer solution upon the physical structure of the viscous sublayer in a fully-developed two-dimensional channel flow.

c. The study has shown that in the dilute polymer solution the non-dimensional spanwise streak spacing increases as the amount of drag reduction increases. However, the bursting rate of the individual streak adjusts to the value for a Newtonian flow at the reduced wall shear. Thus, the spatially averaged bursting rate is decreased and the production of turbulence is decreased in the drag-reducing flows.

d. Donohue, G. L., "The Effect of a Dilute Drag-Reducing Macromolecular Solution on the Turbulent Bursting Process," Ph.D. Dissertation, Oklahoma State University, May 1972.

Donohue, G. L. and W. G. Tiederman, "The Effect of a Dilute Drag-Reducing Macromolecular Solution on the Viscous Sublayer of a Turbulent Channel Flow," 16 mm silent movie submitted to Engineering Societies Library, 345 East 47th Street, New York, New York.

Donohue, G. L., W. G. Tiederman, and M. M. Reischman, "Flow Visualization of the Near-Wall Region in a Drag-Reducing Channel Flow," submitted to the Journal of Fluid Mechanics.

2. Turbulent Velocity Measurement in Dilute Polymer Solutions with a Laser Anemometer Measuring Individual Realizations

a. W. G. Tiederman and D. K. McLaughlin

b. A dual-scatter laser anemometer measuring individual realizations is being used to determine the turbulent velocities in the viscous sublayer of a drag-reducing channel flow.

c. Mean velocity and the streamwise fluctuation intensity have been successfully measured for y^+ values as low as 3 in a drag-reducing flow.

d. Donohue, G. L., "The Effect of a Dilute Drag-Reducing Macromolecular Solution on the Turbulent Bursting Process," Ph.D. Dissertation, Oklahoma State University, May 1972.

Donohue, G. L., D. K. McLaughlin, and W. G. Tiederman, "Turbulence Measurements with a Laser Anemometer Measuring Individual Realizations," to appear in the Physics of Fluids, November 1972.

UNIVERSITY OF PARIS
Aerodynamics Laboratory
Orsay, France

1. Flow of Drag Reducing Dilute Polymer Solutions

a. J. M. Piau, G. Norgeot, A. Baudry (on leave) and J. P. Benque (on leave)

b. The study is divided into three parts:
(1) flow through small holes bored into a thin plate
(2) total head tube measurements: defect of pressure and visual study of the flow around the probes
(3) drag reduction and degradation in turbulent flow through pipes
The aim of the research is to know whether the solutions behave as simple fluids or not for these flows.

c. Some experimental results have been obtained:
(1) The rate of flow through small holes is modified. It is higher for high Reynolds numbers, then smaller for small Reynolds numbers. It seems too, that there is no jet at all for very small Reynolds numbers.
(2) For times ϕ_e/v smaller than a critical value which depends only on the fluid, similar total head tubes (ϕ_e external diameter, v velocity) give a defect of pressure. The dimensional amount of this defect does not depend only on the fluid.
(3) The critical values obtained in these two flows are modified by degradation of the solutions in turbulent pipe flow.

UNIVERSITY OF TOKYO
Department of Marine Engineering
Tokyo, Japan

1. Study of Flow of Dilute Polymer Solutions

a. Tetsuo Tagori

b. Study on flow of polymer solutions near wall, study on hydrofoil in dilute polymer solutions, and study on measuring methods of flow velocity in polymer solutions.

c. The flow visualization on a square duct flow was carried out by means of magnesia powder. As a result, it was shown that velocity distribution, intensity of turbulence and spectrum in polymer solutions flow differed from fresh water.

The pressure distribution of a two-dimensional hydrofoil was measured in polymer solutions, and shift of pressure distribution, decrease in lift, and increase in drag were obtained.

It was shown that the 10 MH_2 doppler sonar current meter was able to be used in polymer solutions for measurements of flow velocity and turbulence.

d. Study on Local Friction in Flow of Polymer Solutions; Odai, Y. and Tagori, T., Preprint 49th Annual Meeting, Japan Society Mechanical Engineers, No. 710-15, August 1971 (in Japanese).

UNIVERSITY OF TORONTO
Department of Chemical Engineering and Applied Chemistry
Toronto 5, Ontario, Canada

1. Flow Visualization Studies of Drag-Reducing Solutions

a. J. W. Smith, R. L. Hummel, and Vr. Arunachalam

b. High-speed movie pictures of photochromic dye trace lines under turbulent flow conditions are used to obtain the velocity distributions and turbulence intensities for flow in a horizontal pipe. Polyox solutions of various concentrations were studied.

c. The sublayer thickening has been indicated as the main mechanism for the observed drag reduction.

d. Can. J. Chem. Eng. (in press)

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Department of Aerospace Engineering
Blackburg, Virginia

1. Turbulent Flow of Non-Newtonian Fluids

a. E. R. van Driest (now at Rand Corp., Santa Monica, California)

b. Analytical and experimental investigation of drag reduction in pipe flow for solutions of Guar Gum, Polyox, and asbestos fibrils.

c. Theory is advanced that drag-reduction effect is due solely to the non-Newtonian variation of fluid shearing stress with strain.

d. (137)

WASHINGTON UNIVERSITY
Department of Mechanical and Aerospace Engineering
St. Louis, Missouri 63130

1. Turbulence Modification and Drag Reduction in Rigid Particle Colloidal Suspensions

a. W. M. Swanson

b. The effects of characteristic relaxation times of colloidal sols on scale and energy spectra are being investigated, and drag-reduction characteristics measured.

c. Drag reduction is obtained with dilute colloidal suspensions showing non-Newtonian viscosity behavior. No sol degradation is obtained. Turbulence microscale is found to be significantly greater for the sol than for the water solvent at the same flow rates, and more energy is concentrated in the large scale turbulence structure.

d. (105)

UNIVERSITY OF WISCONSIN-MILWAUKEE
College of Applied Science and Engineering
Milwaukee, Wisconsin 53201

1. Mass Transfer in Drag-Reducing Fluid Systems

a. Richard G. Griskey and Gomaa H. Sidahmed

b. The effect of drag-reducing agents on mass transfer in fluid systems was studied. The mass transfer was determined by an electrochemical technique which involved transport of mass from the fluid to the tube wall. It was found that the drag-reducing agents retarded mass transfer in turbulent but not in laminar systems. The effect on mass transfer was shown to be comparable to that on heat transfer. The Wells correlation for heat transfer reducing systems was employed for mass transfer. In addition, correlations for Stanton number were determined for mass transfer in drag-reducing systems.

d. (130)

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13 ABSTRACT

A summary of progress in the achievement of frictional drag reduction is presented in terms of highlights, laboratory activities, and bibliographic entries from the summer of 1971 to the summer of 1972.

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