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FRICTION REDUCTION BY ALGAL AND BACTERIAL POLYMERS

by

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ADMINISTRATIVE STATEMENT

This report is a summary of work on friction-reducing algal and bacterial exudates. Sponsored by the Office of Naval Research, the work was accomplished between April 1966 and July 1970 under ONR Project NR 137-699. Major Allen Jewett, Microbiology Branch, Code 443, was the ONR Program Manager. Additional work in this field, performed during the same period under CNM/DLP(IR)ZR011-01-01, is also reported.

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SUMMARY

Problems

Long-chain polymers have been demonstrated to reduce turbulent flow friction in water. The purpose of this investigation is to study the ability of biological polymers produced by seaweeds, microscopic algae, and bacteria to reduce friction in water flow. Three areas are of interest: (1) Can polymers of biological origin account for the reported unexplainable variations in hydrodynamic test facilities? (2) Can biological polymers be used for friction-reduction applications? (3) Can friction-reduction measurements be used to quantitate and characterize biological polymers?

Results

Many seaweeds, microscopic algae, and bacteria were found to produce friction-reducing materials into their culture medium. All water samples tested from inland and marine sources gained friction-reduction ability when enriched with sugar, as a consequence of polysaccharide synthesis by bacteria. Biological polymers, therefore, are the probable cause of the unexplainable variations in hydrodynamic test facilities. Bacterial polysaccharides were more effective than seaweed extract at low concentrations for friction reduction, but both were much less effective than synthetic polymers. Turbulent-flow frictional measurements were found to be sensitive for detection, measurement, and partial characterization of long-chain polymers.

Recommendations

Water in hydrodynamic test facilities should be maintained free from algal blooms and organic contaminants in order to prevent friction-reducing polymer production by algae and bacteria. Seaweed extracts and algal and bacterial polysaccharides could be used in friction-reduction applications; however synthetic polymers are generally much more effective and less expensive. The friction-reduction technique is a rapid and effective procedure for the detection and quantification of long-chain polymers, and further uses in polymer chemistry and molecular biology should be explored.

CONTENTS

INTRODUCTION

Drag reduction, friction reduction, or the Toms effect are terms used to describe the flow situation when high polymers are present in flowing liquids (Ref. 1, 2, 3, and 4). High polymers decrease the turbulence intensity, and therefore allow the liquid to flow with less resistance. In many instances, only a few parts per million of polymer is needed in order to reduce the friction by 50% to 60% or more. Thus numerous engineering applications seem possible. These include increased flow rates in pumping applications and increased speeds or decreased power requirements for a body traveling through water.

Unexplainable variations in the turbulent-flow properties of water in hydrodynamic test facilities and ocean waters have perplexed hydrodynamacists for many years. Newton (Ref. 5) discussed fluctuations in towing tanks and presented data obtained between 1887 and 1965 from the Haslar towing tank in England. The same towing test model was used during this period with a maximum fluctuation of 14% decrease in friction measured from the original value. Fluctuations in water friction were also shown for the Fort Steyne towing tank, England (Ref. 6). Other reports have cited instances where a ship would have different power requirements at different times, or where sister ships would perform differently during trials. As demonstrated in this report, these anomalies can now be explained in terms of the drag-reduction phenomenon, and can be attributed to dissolved long-chain polysaccharides exuded by algae and bacteria.

After the discovery that microbial polymers are effective in the reduction of turbulent-flow friction, a search was begun for algal and bacterial polymers which may be suitable for friction-reduction applications. The only long-chain biological polymers which can be produced cheaply and in large quantities are the polysaccharides, and these were therefore studied in detail.

The turbulent-flow rheometer, a miniature pipe-flow apparatus, was used for friction-reduction tests. Its function is discussed in the following section, and its uses as an analytical tool are elucidated in the Appendix. The next section deals with friction reduction by seaweeds, phytoplankton, and bacteria, and suggests how these biological polymers might affect hydrodynamic testing. And finally, there is a discussion of the possible engineering applications of friction-reducing biological polymers and the limitations of these polymers for such applications.

DESCRIPTION OF THE TURBULENT-FLOW RHEOMETER

The turbulent-flow rheometer, an instrument developed at the Naval Undersea Research and Development Center (NUC), has proven valuable for many applications in hydrodynamic testing, polymer chemistry, and biological research. It was used to measure the friction-reduction ability of algal and bacterial cultures, purified polymers, and water from test facilities. The use of the turbulent-flow rheometer as an analytical tool is discussed in the Appendix.

Since the turbulent-flow rheometer was a key equipment item in obtaining the results described in this report, a brief description of the instrument and its principle of operation is included here. All other experimental details as, for example, to media and incubation techniques may be found in the publications listed as references.

Figure 1 is a schematic diagram of the turbulent-flow rheometer. In essence the apparatus consists of a motor-driven syringe that forces the test solution through a small pipe, of diameter d, at a given velocity, V, such that, with η the kinematic viscosity, the Reynolds number $Re = Vd/\eta$ is completely in the turbulent regime. The Reynolds number in the NUC tests was maintained at 14,000. The percent of

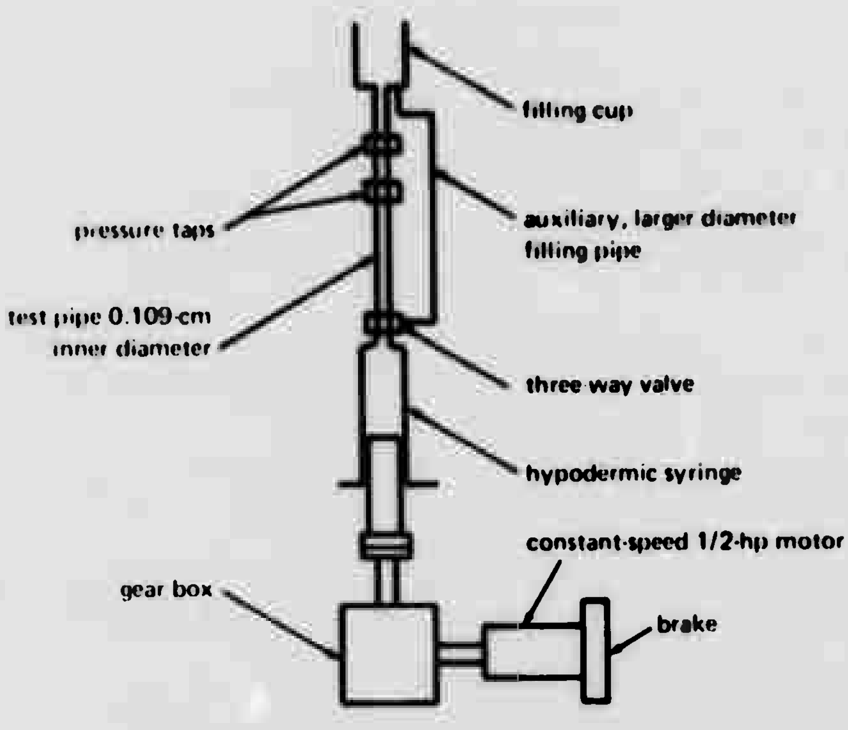

Figure 1. Schematic of turbulent-flow rheometer. The experimental measurement consists of recording differential pressure at the points marked "pressure taps."

friction reduction was determined by measuring the differential pressure, ΔP, at two points along the pipe, first for the test solution and then for the solvent (water or culture media). Then

$$\text{Percent friction reduction} = 100(1 - \Delta P_t/\Delta P_s)$$

where ΔP_t is the differential pressure measured with the test solution and ΔP_s is that pressure measured under the same conditions with the solvent. Experimentally it is known that at the Reynolds number of the instrument a maximum friction reduction of 65% to 70% can be obtained. (At higher Reynolds numbers, higher friction reductions are possible.) Thus in the use of the instrument it is occasionally necessary to dilute a test solution by factors of 10 or more in order to demonstrate, as in bacterial cultures, the continual production of drag-reducing polymer. Otherwise the polymer would accumulate in such a quantity that a maximum drag-reducing measurement could not be obtained.

Finally, it is possible to repeat the turbulent-flow rheometer measurement over and over ("multiple passes"). Repeated measurements induce repeated mechanical shear on the macromolecules in solution, breaking a certain proportion of the polymer chains and reducing the average molecular weight. The friction-reducing effect is then diminished as a function of the number of passes through the instrument. The rate of diminished friction reduction is dependent, however, on the type of polymer present, since some molecules are much more resistant to scission than others.

FRICTION REDUCTION BY BIOLOGICAL POLYMERS

The ability of seaweeds, phytoplankton, and bacteria to produce measurable quantities of friction-reducing materials has several implications. One of the more important of these implications is that biological polymers present in hydrodynamic test facilities may alter the frictional properties of the water. A basic understanding of organisms capable of producing friction-reducing polymers is therefore essential.

Seaweeds

Seaweeds were examined for friction-reducing capabilities by using hot water to extract polymer from intertidal specimens and by testing commercially available seaweed derivations (Ref. 3 and 7). Table 1 shows the results obtained from intertidal seaweed extracts. Many specimens were found to possess extractable polymers which reduced turbulent friction up to 60%. Experimentally it has been shown that

Table 1. Friction reduction of extracts from intertidal collections (1 gram dry weight seaweed per 100-ml water).

Genus	Location[a]	Month	Friction reduction, %: In distilled water	Friction reduction, %: In seawater
		(A) Chlorophyta		
Ulothrix	Trondheim, Norway	June	5–20	5–20
Ulva	Corona del Mar	Nov	0–5	0–5
Ulva	Pacific Grove	Feb	20–40	not tested
Ulva	Pacific Grove	Aug	5–20	20–40
Ulva	Pacific Grove	Aug	20–40	5–20
Ulva	Bandon, Oreg.	Aug	5–20	0–5
Ulva	Ft. Bragg	Aug	5–20	0–5
Ulva	Mediterranean	Jan	5–20	0–5
Ulva	Encinitas	July	0–5	0–5
Ulva	Encinitas	May	20–40	0–5
Ulva	Asilomar	Aug	40–60	40–60
Ulva	Laguna	June	40–60	20–40
Enteromorpha	Trondheim, Norway	June	5–20	5–20
Enteromorpha	Trondheim, Norway	June	5–20	20–40
Enteromorpha	Trondheim, Norway	June	5–20	0–5
Enteromorpha	Bergen, Norway	June	5–20	5–20
Enteromorpha	Encinitas	May	0–5	0–5
Chaetomorpha	Laguna	July	0–5	0–5
Cladophora	Pacific Grove	Feb	0–5	not tested
Cladophora	Pacific Grove	Aug	5–20	5–20
Cladophora	Morro Bay	Aug	0–5	5–20
Caulerpa	Mediterranean	Dec	5–20	20–40
		(B) Phaeophyta		
Dictyota	Cabrillo	Jan	0–5	5–20
Ilea	Bandon, Oreg	Aug	40–60	40–60
Ilea	Bandon, Oreg.	Aug	20–40	20–40
Laminaria	Encinitas	July	0–5	0–5
Macrocystis	Carpenteria	Sept	0–5	5–20
Macrocystis	Laguna	July	0–5	0–5
Postelsia	Ft. Bragg	Aug	20–40	5–20
Egregia	Cabrillo	Jan	0–5	0–5
Egregia	Cabrillo	Dec	0–5	not tested
Ascophyllum	Rye, N.H.	Apr	5–20	5–20
Fucus	Portland, England	July	5–20	5–20
Fucus	Bergen, Norway	June	20–40	5–20
Fucus	Bergen, Norway	June	5–20	20–40
Fucus	Rye, N.H.	Apr	5–20	5–20
Fucus	Coney Island, N.Y.	Jan	0–5	0–5
Fucus	Kittery, Maine	July	0–5	0–5
Hesperophycus	Laguna	Oct	20–40	20–40
Hesperophycus	San Clemente Is.	Aug	0–5	5–20
Pelvetia	San Clemente Is.	Aug	0–5	0–5
Pelvetia	Laguna	June	5–20	0–5

contd

Table 1. Contd.

Genus	Location[a]	Month	Friction reduction, %	
			In distilled water	In seawater
(B) Phaeophyta (contd)				
Pelvetia	Pacific Grove	Aug	20-40	5-20
Pelvetiopsis	Ft. Bragg	Aug	20-40	20-40
Pelvetiopsis	Trinidad	Aug	40-60	40-60
Cystoseira	San Clemente Is.	Aug	0-5	0-5
(C) Rhodophyta				
Porphyra	Ft. Bragg	Aug	40-60	40-60
Porphyra	Morro Bay	Aug	20-40	40-60
Porphyra	Pacific Grove	Aug	20-40	20-40
Porphyra	Laguna	July	20-40	20-40
Porphyra	Laguna	July	5-20	5-20
Porphyra	Laguna	Aug	40-60	5-20
Bossiella	Encinitas	May	0-5	0-5
Bossiella	Cabrillo	Jan	5-20	0-5
Corallina	Encinitas	July	0-5	0-5
Corallina	Cabrillo	Jan	40-60	0-5
Corallina	Cabrillo	Feb	20-40	0-5
Corallina	Pacific Grove	Feb	5-20	not tested
Lithrothrix	Cabrillo	Mar	5-20	not tested
Gratelupia	Morro Bay	Aug	40-60	20-40
Prionitis	Cabrillo	Jan	5-20	20-40
Prionitis	Cabrillo	Dec	20-40	5-20
Prionitis	Cabrillo	Dec	0-5	0-5
Plocamium	Cabrillo	Dec	0-5	0-5
Plocamium	Laguna	June	20-40	5-20
Gymnogongrus	Cabrillo	Jan	40-60	20-40
Gymnogongrus	Cabrillo	Dec	20-40	40-60
Stenogramma	Laguna	July	40-60	20-40
Stenogramma	Pacific Grove	Aug	20-40	40-60
Gigartina[b]	....	....	20-40	20-40
Halosaccion	Ft. Bragg	Aug	20-40	5-20
Rhodymenia	Lake Dark Harbor, N.B.	....	20-40	0-5
Rhodymenia	Trinidad	Aug	20-40	40-60
Callithamnion	Laguna	Aug	5-20	0-5

[a] All locations are in California except as otherwise noted.

[b] Twenty-two samples were collected from various points in California and their percent of friction reduction was averaged.

polymers having molecular weights above 50,000 must be present to produce this effect (Ref. 3). Friction-reduction ability varies considerably within each genus.

Of the 95 intertidal samples collected, over 80% produced substantial friction reduction when extracted in either distilled water or seawater. The red seaweeds were especially prominent in this regard: over 90% of the red algal showed pronounced friction reduction. In fact, over half of the Rhodophyta samples showed friction reduction above 40%.

Results for 0.1% solutions of seaweed derivations are shown in Table 2, and friction-reduction effectiveness of four extracts as a function of concentration is illustrated in Fig. 2. These polysaccharides can reduce friction more than 50% at increased concentrations. Nevertheless, much greater concentrations are required for seaweed polysaccharides than for many other polysaccharides to produce the same friction-reduction effectiveness.

Table 2. Friction reduction of 0.1% solution of seaweed derivatives.

Name	Type	Source	Friction reduction, %
Carrageenan	Sea kem 7	Marine Colloids, Inc.	46.0
Carrageenan	Gelcarin HWG	Marine Colloids, Inc.	51.0
Calcium carrageenan	Gelcarin HMR	Marine Colloids, Inc.	51.5
Sodium carrageenan	Viscarin 271206	Marine Colloids, Inc.	62.0
Lambda carrageenan	Viscarin 402	Marine Colloids, Inc.	53.0
Carrageenan	Stabiloid 15	Stein, Hall Co., Inc.	57.0
Carrageenan	Stamere NK	Meer Corp.	58.0
Carrageenan	IK-FV-CP	Burtonite Co., Inc.	60.0
Eucheuma cottonii	RELA 5166	Marine Colloids, Inc.	29.5
Agardhiella	RELA 5167	Marine Colloids, Inc.	59.5
Eucheuma spinosum	Gelcarin SI 672106	Marine Colloids, Inc.	32.0
Furcellaran	Series No. 44A	Burtonite Co., Inc.	46.5
Sodium alginate	.....	Norwegian Inst. Seaweed Res.	61.5

Phytoplankton

Phytoplankton cultures were effective in friction-reduction ability when grown in defined medium or soil extract medium (Ref. 7 and 8). Table 3 shows that representatives of many major phytoplankton groups could be found which excrete friction-reducing materials into their culture media. These algae were found by trial and error: closely related species often did not produce friction-reducing materials. For example, among the diatoms, *Chaetoceros didymus* and *C. affinis* were definitely friction-reducing while *C. pelagicus*, *C. lorenzianus*, *C. compressus*, and *C. decipiens* exhibited only traces of reduction or no reduction at all. In some species (for example, *Prorocentrum micans*) the friction-reduction materials were found to be most pronounced as the cultures approached senescence. In other species, such as *Chaetoceros*, the extracellular materials production accompanied exponential growth. In *Porphyridium* the extracellular friction-reduction material was secreted copiously

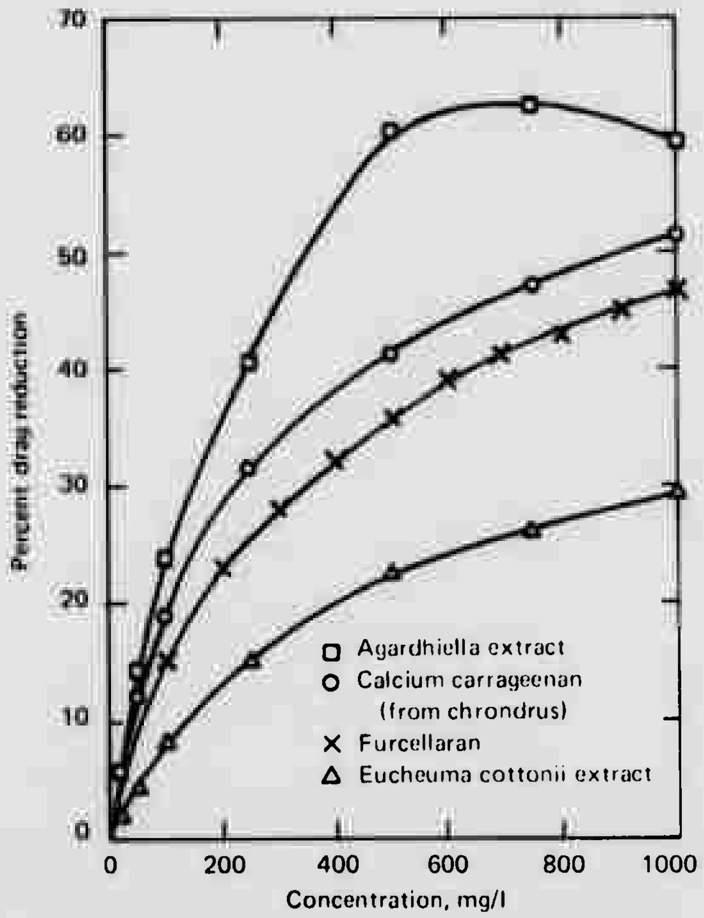

Figure 2. Typical drag-reduction curves obtained with solutions of commercial seaweed extracts.

Table 3. Friction reduction of phytoplankton cultures.

Organism	Friction reduction,[a]
Chlorophyta	
Chlorella stigmataphora, LB 993	40-60
Bacillariophyta	
Chaetoceros didymus	20-40
Chaetoceros affinis	5-20
Pyrrophyta	
Exuviella cassubica	5-20
Prorocentrum micans, LB 1003	5-20
Rhodophyta	
Porphyridium cruentum, 161	40-60
Porphyridium sp. (Lewin), 637	40-60

[a] Average of over 25 cultures extending over at least 1 year.

from the time the culture was inoculated (Fig. 3). A culture of *Porphyridium cruentum*, stored in the refrigerator for over a year, retained a friction-reduction value of 60%.

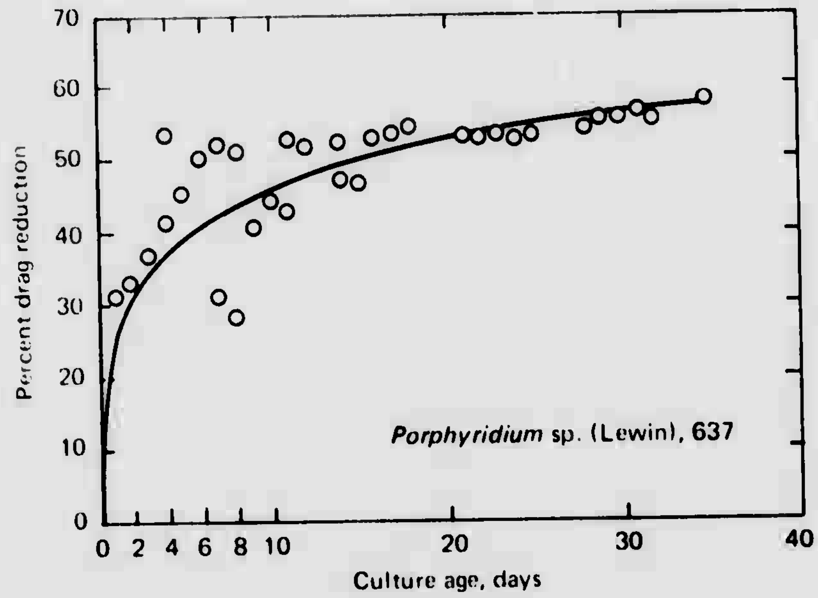

Figure 3. Drag reduction obtained with cultures of *Porphyridium* sp.

Bacteria

Several pure bacterial cultures were grown in a nutrient medium containing protein hydrolysates, yeast extract, sugars, and glycerol to show that extracellular polymers produced by bacteria could change the friction. Friction reduction was measured during the growth cycle. Bacterial growth was measured by the optical density of the culture. Three different trends were noted.

Pseudomonas sp. (Fig. 4) exhibited a continuous increase in friction reduction during the logarithmic growth phase with no further increase during subsequent growth. The culture of *Bacillus* sp. (Fig. 5) showed an increase in friction-reduction ability to the start of the stationary growth phase, after which a substantial decrease took place. Friction reduction for *Neisseria* sp. increased many hours after the start of the logarithmic growth phase (Fig. 6). By diluting the bacterial culture 1 : 10 with additional media it was possible to show, as in Fig. 6, that polymer production continued well after the logarithmic growth phase. The above results illustrate that friction-reducing extracellular polysaccharide synthesis and degradation occurs in bacteria. Polymer production is variable during the growth cycle according to species (Ref. 9).

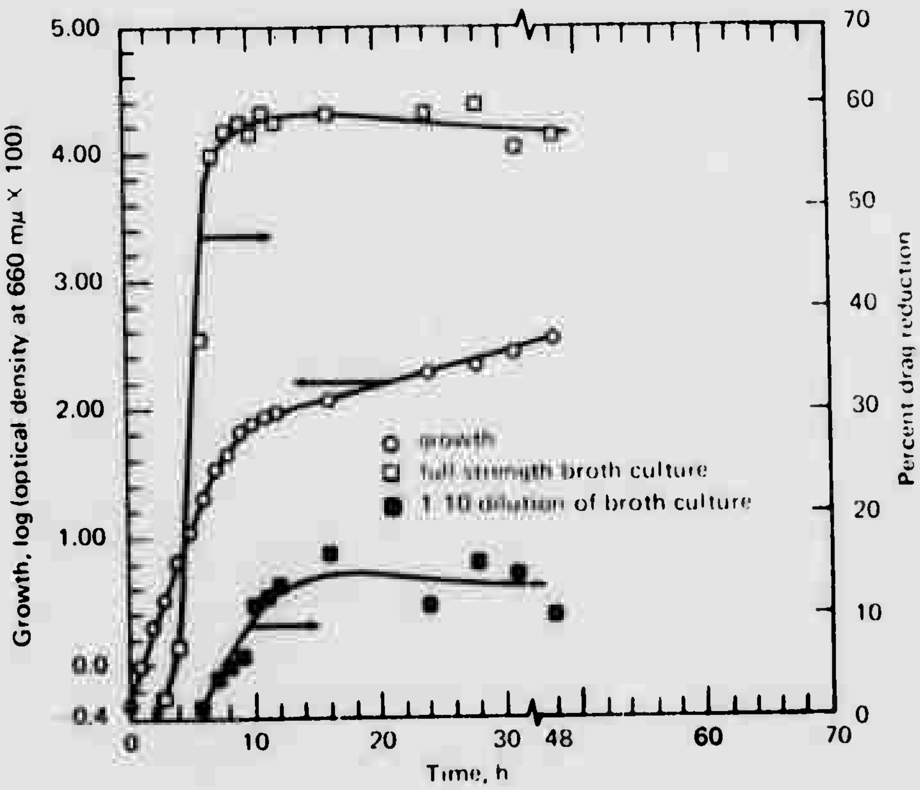

Figure 4. Drag reduction by *Pseudomonas* species in relation to growth.

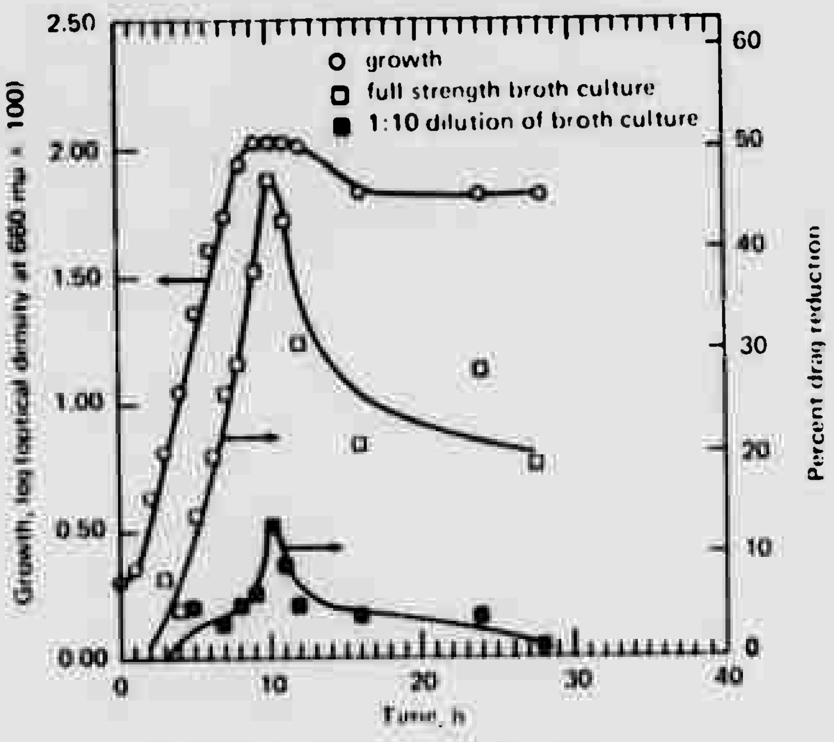

Figure 5. Drag reduction by *Bacillus* species in relation to growth.

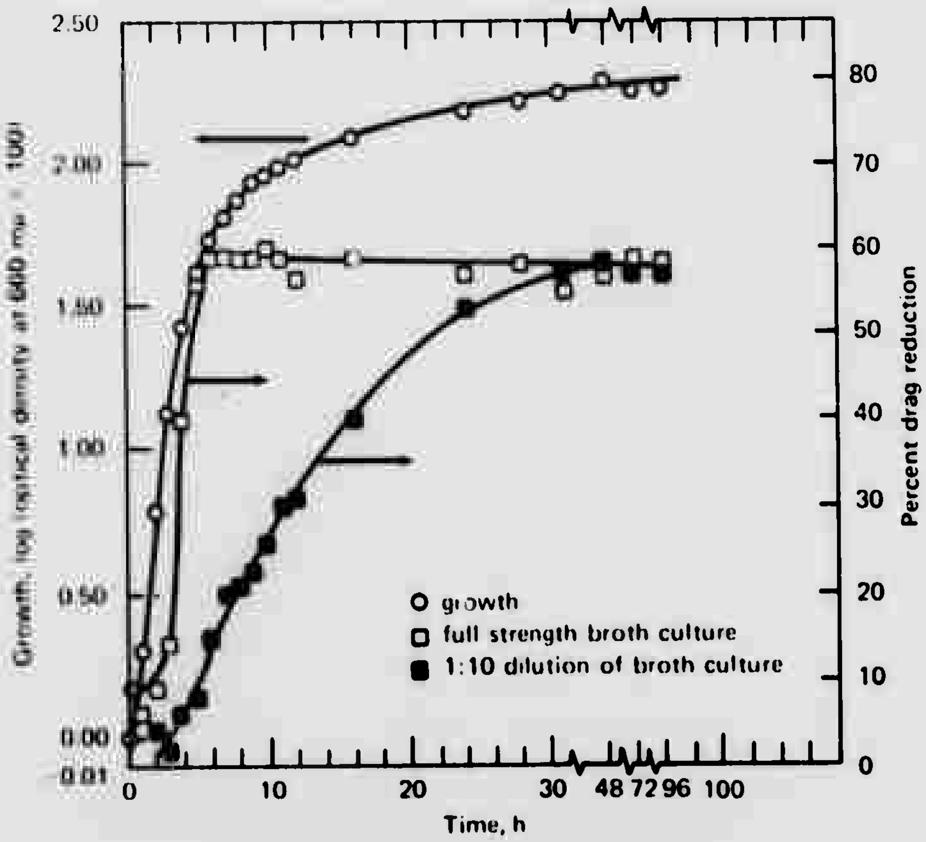

Figure 6. Drag reduction by *Neisseria* species in relation to growth.

Drag-reducing polymer can be produced by psychrophilic (optimum growth temperature below 20°C), mesophilic (optimum between 20°C and 45°C), and thermophilic (optimum above 45°C) bacteria. The marine psychrophile, 20-PFD-2, an encapsulated gram-negative rod isolated from Antarctic waters, had a growth optimum of 15°C and a maximal temperature for growth of 35°C (Fig. 7). The optimum temperature for drag-reducing polymer production of the culture was also 15°C. *Vibrio marinus* MP-1, a marine psychrophilic bacterium with an optimum growth temperature of 15°C and a maximal growth temperature of 20°C, exhibited no drag reduction at 15°C until 10 days, after which drag reduction increased to above 50%.

Mesophile isolates PF-3 and SLJ-1 had growth and drag reduction optima of approximately 30°C (Fig. 8 and 9). The thermophilic fresh water bacterium, *Bacillus stearothermophilus*, with a growth optimum of 60°C and a minimal growth temperature of 40°C, produced drag reductions greater than 15% after 48 hours when grown in broth. These studies demonstrate that drag-reducing polymers can be produced from bacteria and can exist in aqueous psychrophilic, mesophilic, and thermophilic environments (Ref. 10).

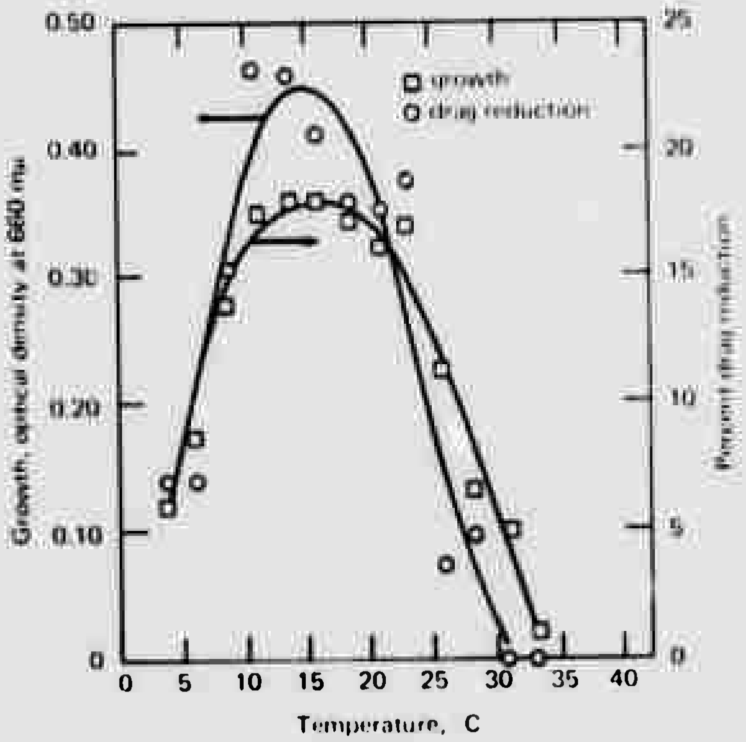

Figure 7. Growth and drag reduction by cultures of marine bacterium 20-PI D-2 after 40 hours at various growth temperatures.

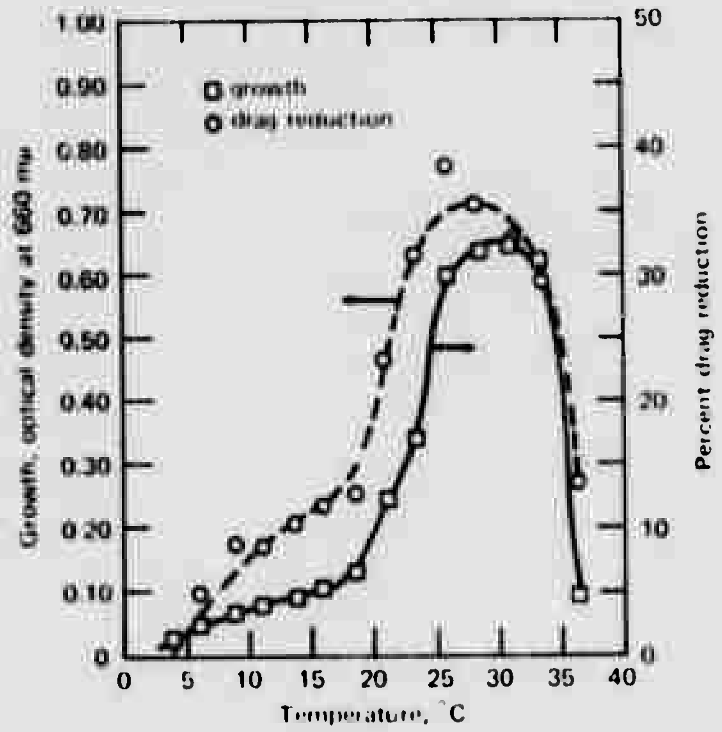

Figure 8. Growth and drag reduction by cultures of marine bacterium PI-3 after 20 hours at various growth temperatures.

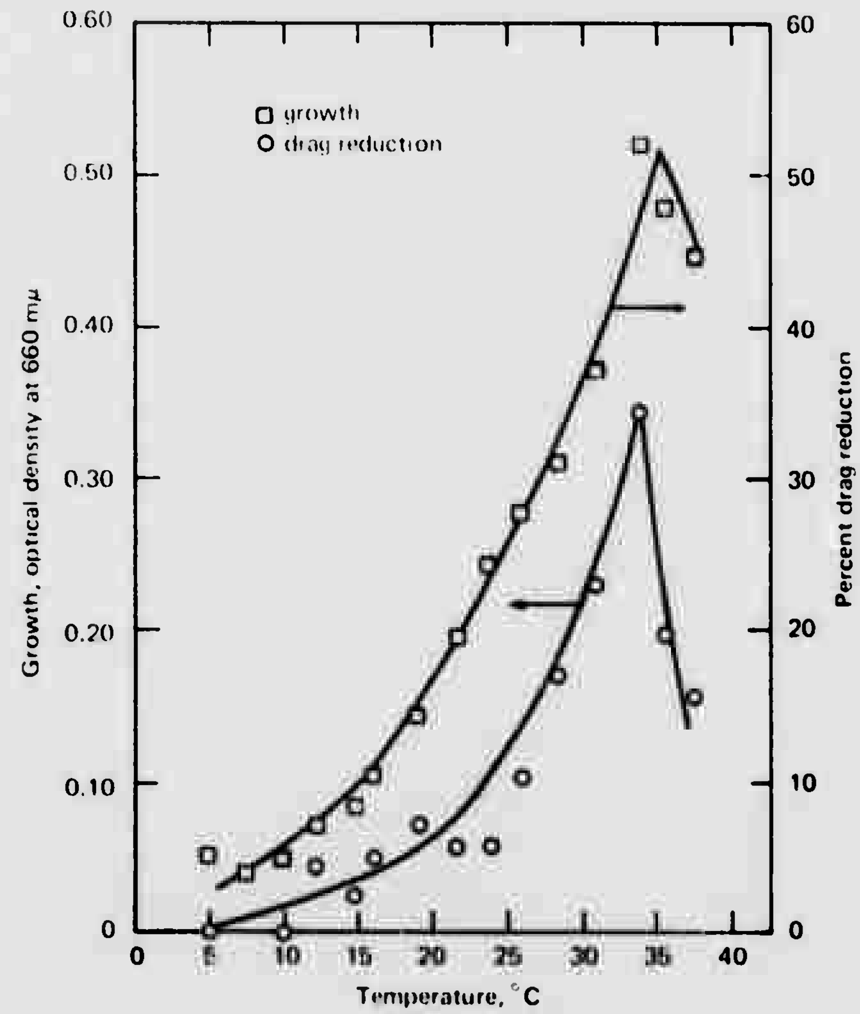

Figure 9. Growth and drag reduction by cultures of marine bacterium SLJ-1 after 14 hours at various growth temperatures.

BIOLOGICAL POLYMERS AFFECTING HYDRODYNAMIC TESTING

In view of the desirability of maintaining constant test conditions in hydrodynamic test facilities, it is important to realize the potential of algae and bacteria in the alteration of turbulent water friction. Cases of reduced friction in towing tanks have been reported (Ref. 5 and 6). Although friction-reduction anomalies have not been detected in water samples taken directly from testing facilities, many algae and bacteria with the ability to synthesize friction-reducing polymers have been isolated from these water samples (Ref. 7, 8, 9, 10, 11, and 12). Under laboratory conditions algae and bacteria may reduce frictional properties of their medium by more than 50%. To preclude the occurrence of altered frictional properties in test facilities, algal blooms should be prevented.

Table 4 shows several algae isolated from 4 test facilities, and Table 5 lists bacterial isolates from 11 facilities, all organisms being effective drag reducers.

Table 4. Algae isolated from test facilities.

Facility	Predominant algae present	Maximum drag reduction, %
Ship tow tank, National Physical Laboratory, Feltham, England	Bright green, spherical *Chlorococcum humicola*	66.1
Tow tank, Bassin d'Essais des Carenes, Paris, France	Green, spherical, 7.5μ diam. (unknown), *Navicula notha*; *Ankistrodesmus* sp.	8.3
Underwater cableway, Morris Dam, NUC Test Facility, Azusa, Calif.	Green, elliptical *Asterococcus*, *Synedra*	35.8
Transducer calibration facility, Lake Gem Mary, Underwater Sound Reference Division, Naval Research Laboratory, Orlando, Fla.	Green, spiny: *Golenkinia*, green, 1μ diam. (unknown)	46.6

As will be discussed in the next section, bacteria which can synthesize friction-reducing polymers are present in natural waters when sufficient organic contamination exists. It is therefore recommended that sanitary conditions be maintained in test facilities so as to avoid contamination by organic material. As a final check in precise hydrodynamic testing, a water sample should be tested by a sensitive turbulent-flow rheometer to detect possible variations in frictional properties and, if necessary, corrections should then be made.

Table 5. Drag-reducing bacteria from hydrodynamic test facilities.

Facility	Isolate designation	Morphology[a]	Colony consistency[b]		Capsule[c]	Drag reduction,[d] %
			1 day	5 days		
Rotating-beam channel, Admiralty Research Laboratory, Teddington, England	RBC-ARL-1	rod	MB	P		52
	RBC-ARL-2	rod	MB	MB	−	12
	RBC-ARL-3	rod	P	P	+	40
Ship tow tank, National Physical Laboratory, Feltham, England	NPLS-1	rod	M	M	+	14
	NPLS-3	rod	MB	MB	+	38
	NPLW-4	coccus	P	P	+	9

contd

Table 5. Contd.

Facility	Isolate designation	Morphology[a]	Colony consistency[b] 1 day	Colony consistency[b] 5 days	Capsule[c]	Drag reduction,[d] %
Garfield Thomas water tunnel, State College, Pa.	GWT-A	rod	M	M	–	16
	GWD-D	rod	B	B	–	8
Flow tunnel, Naval Underwater Sound Laboratory, New London, Conn.	USL-2B	rod	P	M	+	50
	USL-5	rod	MB	MB	+	5
Main towing basin, Naval Ship Research and Development Center, Carderock, Md.	DTMB-3	rod	P	P	+	50
	DTMB-4	rod	MB	MB	–	31
Tow tanks, Stevens Institute of Technology, Hoboken, N.J.	SIT-2B	rod	MB	B	+	46
	SIT3-2	rod	MB	MB	+	56
	SIT3-3	rod	M	P	+	14
Water tunnel, Naval Ship Research and Development Center, Carderock, Md.	36-T-2	coccus	MB	MB	+	7
	36-T-3	coccus	M	M	+	52
	36-T-P	rod	MB	P	+	57
Transducer calibration facility, Lake Gem Mary, Underwater Sound Reference Division, Naval Research Laboratory, Orlando, Fla.	LGM-2	rod	M	M	+	47
	LGM-4	rod	M	P	+	38
	LGM-5	rod	B	P	–	29
Tow tank, Bassin d'Essais des Carenes, Paris, France	PET-1	rod	B	MB	+	8
	PET-3	rod	MB	MB	+	11
	PET-5	coccus	MB	P	+	52
Open water tunnel, California Institute of Technology, Pasadena, Calif.	CIT-1	rod	M	M	+	32
	CIT-2	rod	MB	MB	–	25
Underwater cableway, Morris Dam, NUC Test Facility, Azusa, Calif.	MDES-1	rod	M	M	+	30
	MDW-4	rod	M	MB	–	8

[a] All isolates were gram negative.

[b] M-moist; B-buttery; MB-intermediate between moist and buttery; P-pituitous (manifested by colony sticking to inoculating loop, producing a string-like extension).

[c] Capsules were discerned from agar-grown colonies after 10 days by indirect staining.

[d] Maximum drag reduction measured in broth cultures up to 5 days.

ENGINEERING APPLICATIONS OF FRICTION REDUCTION

The use of algal polysaccharides for engineering applications of friction reduction does not appear promising due to the relative high concentrations needed to produce good reductions (see Table 2 and Fig. 2). The bacterial polysaccharides are more promising than seaweed extracts, but still much less effective than synthetic polymers. Figure 10 compares four effective bacterial polysaccharides; the plant-derived polysaccharide, guar gum; and two effective synthetic polymers, poly(ethylene oxide) and polyacrylamide. The synthetic polymers are much more effective than the polysaccharides, thus making the use of the latter questionable. A study of the

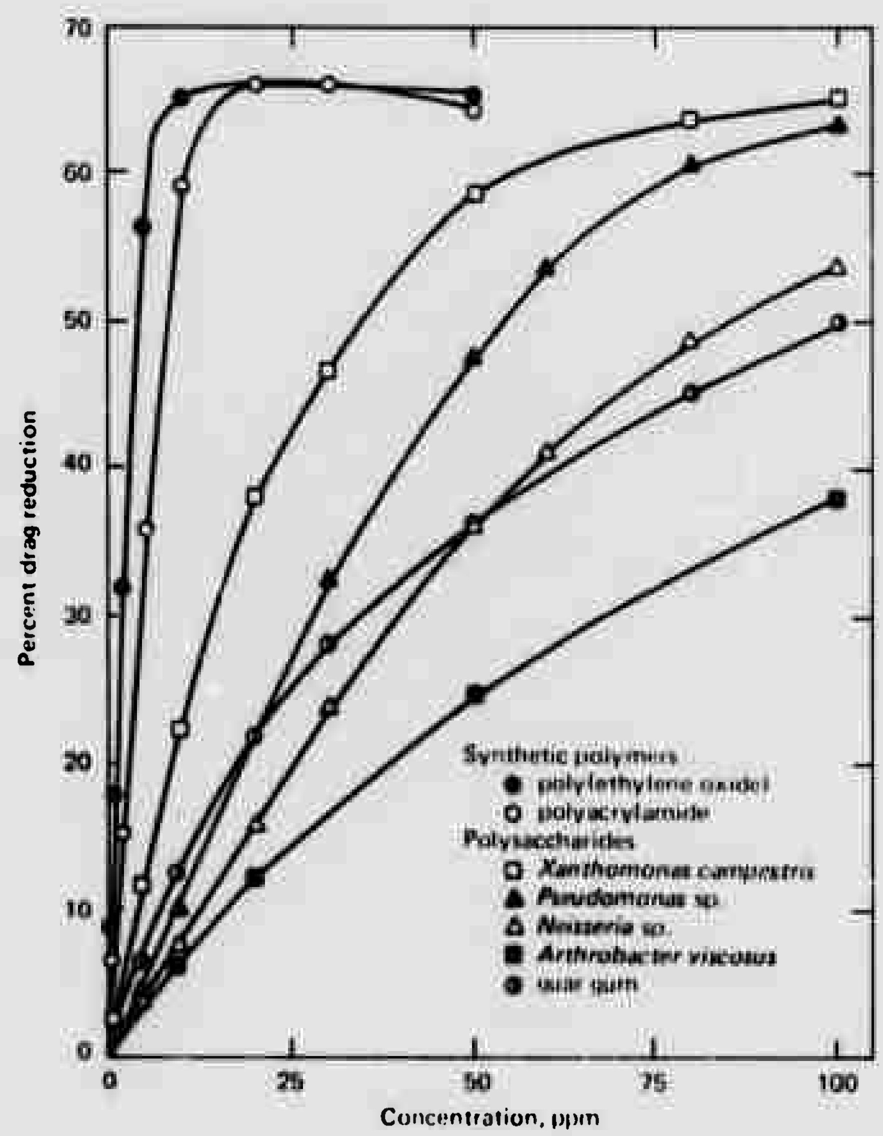

Figure 10. Drag-reduction effectiveness of bacterial polysaccharides, guar gum, and synthetic polymers during one pass through the turbulent-flow rheometer.

stability of bacterial polysaccharides, however, showed possible applications under conditions of high turbulent flow exposure. After prolonged exposure to turbulent flow a 40-ppm solution of *Xanthomonas campestris* (a bacterial polysaccharide) was as effective as poly(ethylene oxide), which degraded substantially (Fig. 11). However, the same bacterial polysaccharide was much less effective than the same concentration of polyacrylamide after prolonged shearing. *Xanthomonas compestris*, with its high stability after prolonged exposure to turbulent flow may serve as a suspending medium in oil-well-drilling applications, and may be useful for specialized friction-reduction applications (Ref. 13 and 14).

When partially purified bacterial polysaccharides are prepared from broth cultures for evaluation as friction reducers, it is desirable to have the highest polymer concentration possible. During several attempts at polysaccharide production the culture medium became acidic with no measurable drag reduction. The addition of sodium bicarbonate, which raised the pH of the medium to about 8, often initiated drag-reducing polymer synthesis. Two freshwater isolates and one soil isolate were investigated for effects of pH on the production of bacterial extracellular drag-reducing polymers (Ref. 15). Figures 12 and 13 show that acidic conditions inhibit polymer production by two isolates, while acidic conditions permitted polymer synthesis by another (Fig. 14).

Buffering is recommended to prevent acidification of the culture medium. The addition of buffers to maintain the pH of the growth medium above 7 is desirable in the isolation and screening of bacteria as possible sources of drag-reducing polymers. This addition will prevent possible inhibition of friction-reducing polymer synthesis which may occur under acidic conditions.

The possibility of an in-situ technique for lessening the turbulent flow frictional properties of water became apparent during water-sugar enrichment studies. It was found that all water samples tested, from inland, ocean, and tap water sources, exhibited friction reduction after sugar enrichment. Apparently bacteria were present that were capable of synthesizing drag-reducing polymers from added sugars. Table 6 lists the percent of drag reduction for sugar-enriched water samples after 30 days. All water sources tested yielded reductions in frictional properties after 30 days, ranging from 8% to 58%. Unfortunately, after 18 months several of the samples lost their friction-reduction properties, indicating the unreliability of the technique over extended periods. Then, too, friction reductions for several samples were only about 10% at 30 days, which is too low to be very useful.

Figure 15 shows the results for sucrose enrichment of 5 gallons of tap water with and without the addition of 1 gram of garden soil. Friction reduction ability for tap water without soil continued to increase steadily and reached 43% friction

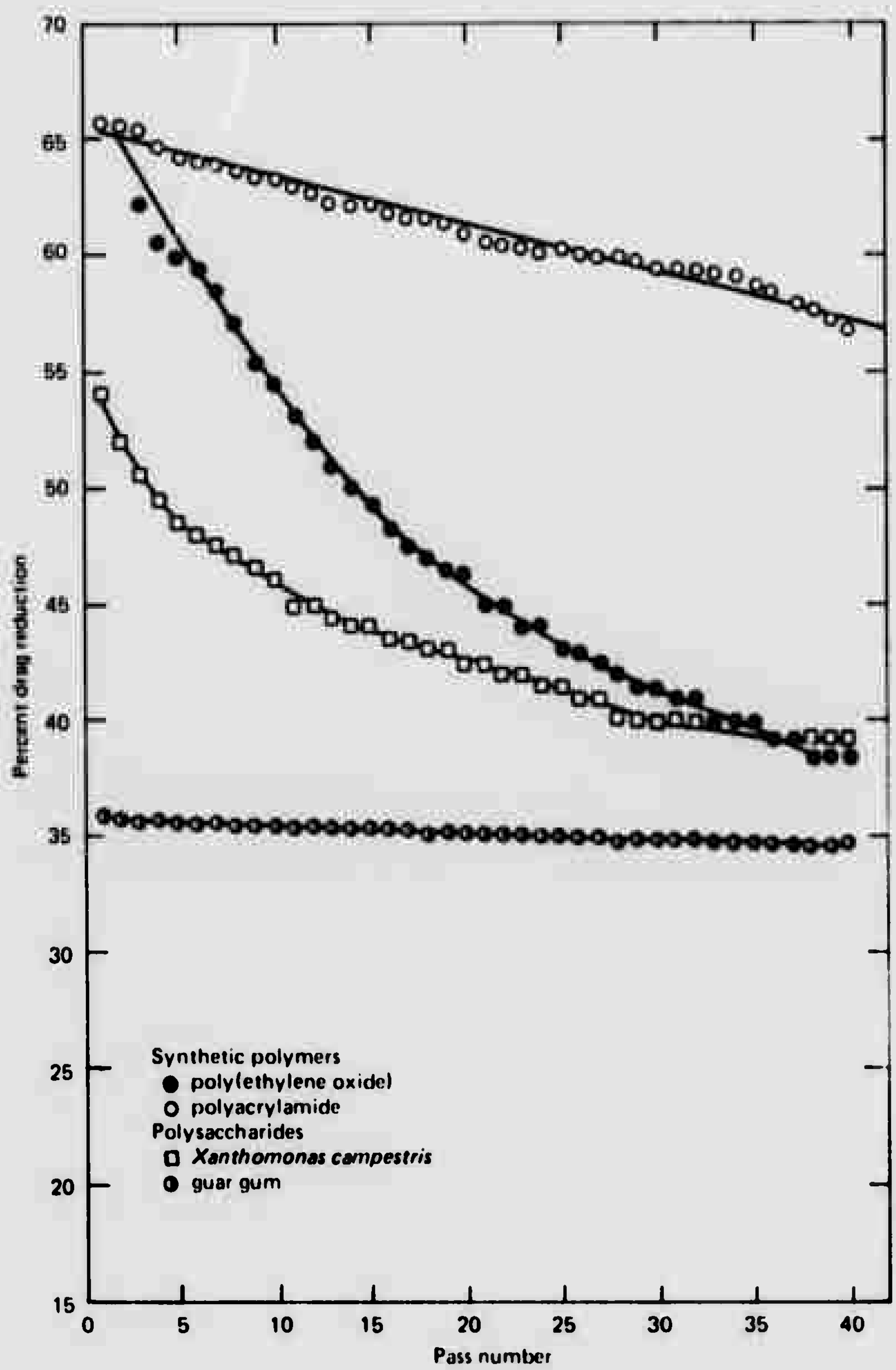

Figure 11. Drag-reduction effectiveness of bacterial polysaccharide, guar gum, and synthetic polymers during repeated passes through the turbulent-flow rheometer.

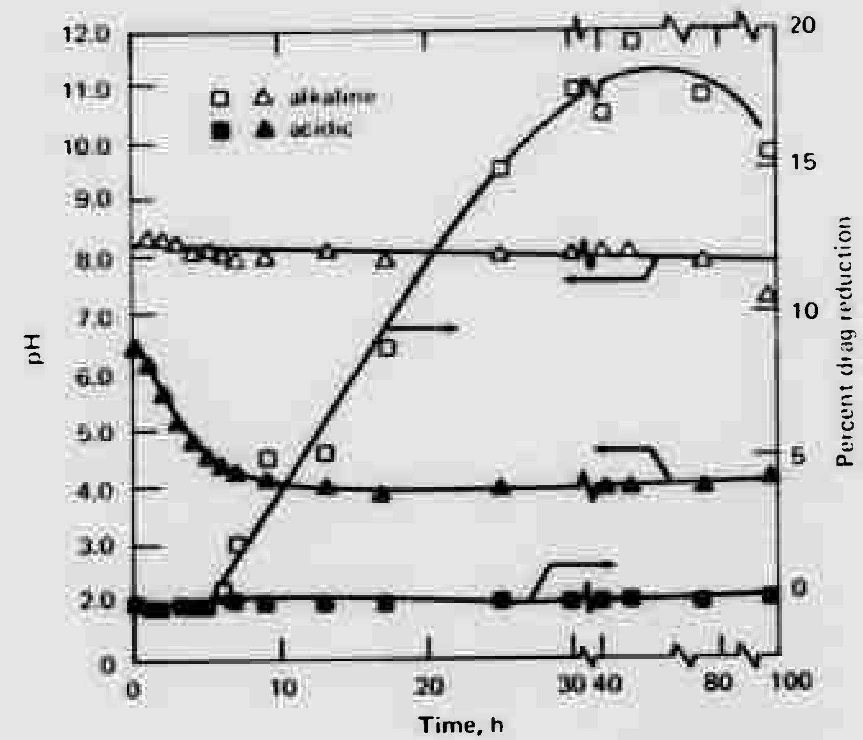

Figure 12. Drag reduction by freshwater isolate FTTS-3 in relation to culture age under alkaline and acidic conditions. Both cultures were tested directly at various times for drag reduction, pH, and growth. Growth (not shown) was considerably less under acidic conditions.

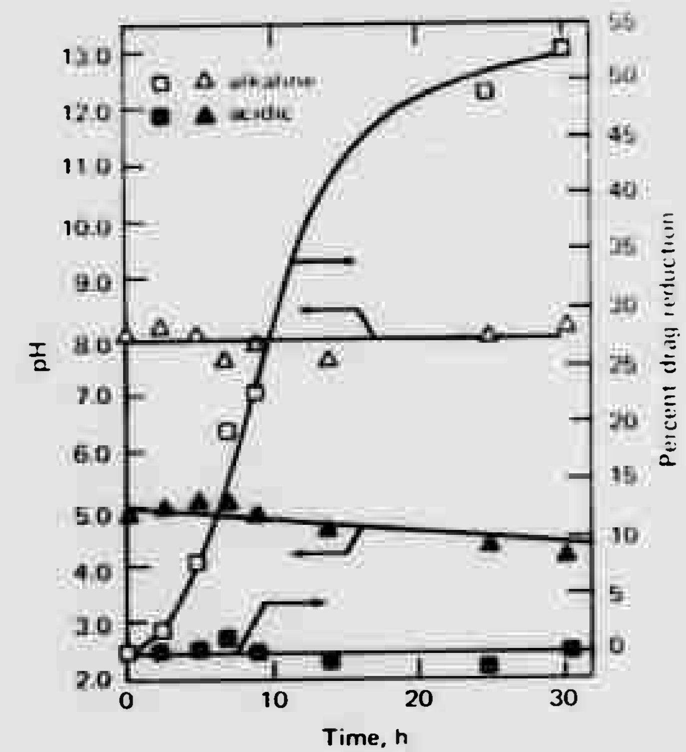

Figure 13. Drag reduction by freshwater isolate USL-2B in relation to culture age under alkaline and acidic conditions. Both cultures were tested directly at various times for drag reduction, pH, and growth. Growth (not shown) at both pH values was similar.

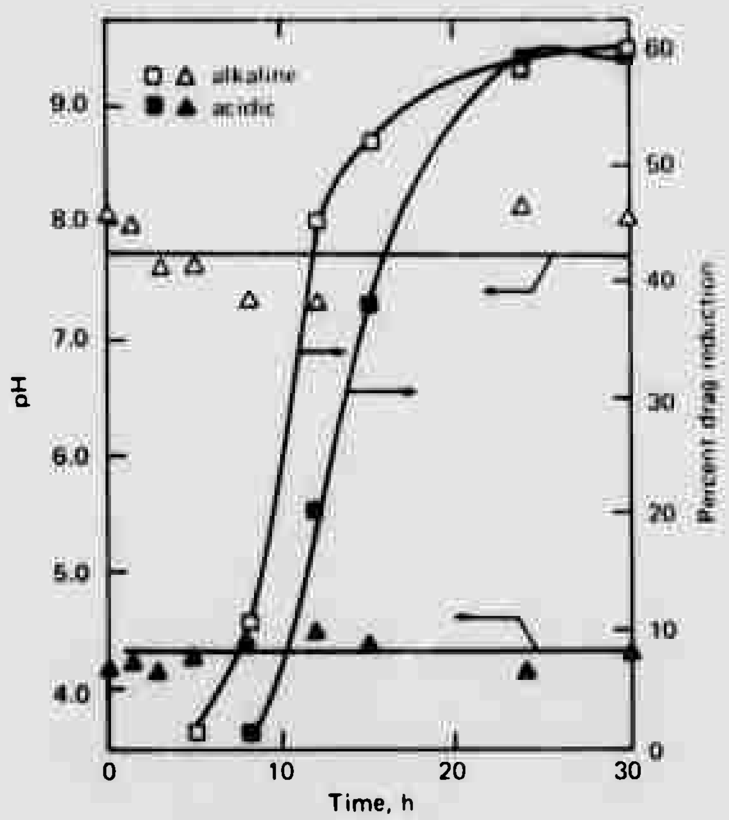

Figure 14. Drag reduction by soil isolate HS-1 in relation to culture age under alkaline and acidic conditions. Both cultures were tested directly at various times for drag reduction, pH, and growth. Growth (not shown) at both pH values was similar.

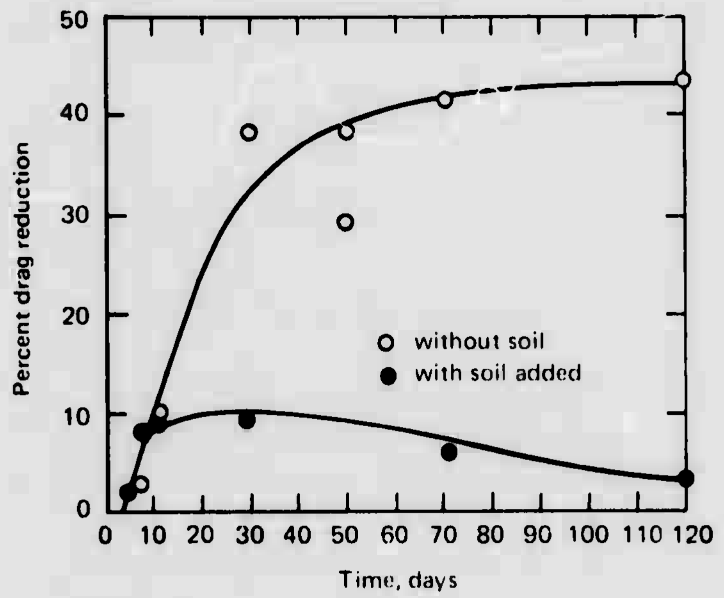

Figure 15. Drag-reduction effectiveness of 5% sucrose-enriched tap water.

Table 6. Drag reduction by sugar-enriched natural waters.

Source	Percent drag reduction[a]
Walden Pond, Mass.	15
Klootchie Creek, Oreg.	41
Lake Gem Mary, Orlando, Fla.	48
San Gabriel River, Calif.	16
Own Head Springs, Death Valley, Calif.	33
Saratoga Springs, Death Valley, Calif.	10
Ocean water near Catalina, Calif.	29
Lake Arrowhead, Calif.	10
Warm Springs Creek, Oreg.	54
Coffinberry Lake, Oreg.	46
Zig Zag River, Oreg.	30
Cullaby Lake, Oreg.	46
Santiam River, Oreg.	53
Neacoxie Lake, Oreg.	25
Morris Dam, Calif.	40
St. Anthony Falls, Minn.	57
Ocean water near Palos Verdes, Calif.	55
Ocean water near San Pedro, Calif.	58
Ocean water near Samuel H. Boardman State Park, Oreg.	58
Ocean water near Yachats, Oreg.	57
Yaquina Ray, Oreg.	58
Rainbow Falls, Hilo, Hawaii	30
Pond Water, Hilo, Hawaii	38
Akaka Falls, Hilo, Hawaii	30
Visalia Aquaduct, Calif.	35
Stream water, Fort Tejon, Calif.	40
Kaveah River, Calif.	8
Ocean water, La Bufadora, Baja, Calif.	17

[a] Water samples enriched with 0.5% glucose and sucrose were tested for drag reduction (for periods up to 30 days), and the maximum value was listed.

reduction after 120 days. A slight turbidity developed after 1 week, but settled out, leaving the water clear. Water with soil added, however, showed a different trend. After several days considerable turbidity developed which continued to increase with the formation of large masses of insoluble aggregates and pungent volatile products. After 120 days friction reduction was less than 5%.

From these results it appears that when sufficient concentrations of natural nutrients are present added sugar provides the microbial population with energy and carbon skeletons for cell division and the synthesis of matrices in aggregate formation. However, when nutrients are minimal, sugar enrichment affords energy and carbon skeletons primarily for the synthesis of soluble polysaccharides necessary to cause friction reduction. The possibility thus arises of utilizing this effect in emergency storage reservoirs for fire-fighting, in order to provide a low-friction supply of water which would reduce frictional losses in piping and hoses and hence increase the rate of flow of water to fight fires. This idea is, of course, in the conceptual stage only, and many engineering problems remain to be solved before the technique can be recommended.

FINDINGS

1. The friction-reduction measurements were found sensitive for the detection of polysaccharides with linear conformations and molecular weights greater than 50,000.

2. Some seaweeds, phytoplankton, and bacteria may produce materials which reduce turbulent-flow friction.

3. By producing polymers in a culture medium, algae and bacteria have reduced friction by more than 50%.

4. Bacteria which can synthesize friction-reduction polymers from simple sugars were found in all water samples tested.

5. Acidic pH conditions inhibited friction-reduction polymer synthesis by some bacteria.

CONCLUSIONS

1. Turbulent-flow measurements can be used to show the presence of certain biological macromolecules (polymers) and to aid in their partial physical characterization.

2. Polymers produced by algae and bacteria in hydrodynamic test facilities may alter the turbulent-flow properties of the water and thus affect test results.

3. Algae and bacteria may be a source of dissolved high-molecular-weight substances in fresh and marine waters.

4. Acid conditions may prevent the synthesis of polysaccharides by some bacteria.

5. Bacteria which have the ability to produce friction-reduction polymers appear to be omnipresent in water.

6. Polysaccharides may have engineering applications for friction reduction, but they are generally less effective than synthetic polymers.

RECOMMENDATIONS

1. Friction-reduction measurements should be explored as a tool in biological and chemical research to measure and characterize long-chain polymers.

2. Waters in hydrodynamic test facilities should be tested for the presence of friction-reduction polymers and maintained free from organic materials which may serve as a source for the production of these polymers by microorganisms.

3. In the laboratory preparation of bacterial polysaccharides a buffer should be added to maintain slightly alkaline pH values to prevent the possible inhibition of polymer synthesis which may occur under acidic conditions.

4. Synthetic polymers should be considered in preference to the polysaccharides for most friction reduction applications.

Appendix

THE TURBULENT-FLOW RHEOMETER AS AN ANALYTICAL TOOL

The simplicity and sensitivity of the turbulent-flow rheometer in measuring friction reduction (Ref. 16 and 17) make it a powerful tool for polymer chemistry and biological and hydrodynamic applications.

Since friction reduction effectiveness is directly related to the effective length-to-width ratio of the polymer molecule (the degree of linearity), a simple friction-reduction determination for an unknown solution will give a qualitative indication if a linear macromolecule is present. Friction reduction produced by an unknown solution indicates only that a linear polymer is present, while high friction-reduction values for known polymer concentrations can give estimates as to the length-to-width ratio and consequently molecular weight (Ref. 18 and 19). A high friction reduction by low polymer concentrations indicates long-chain polymers, while low values for high polymer concentrations suggest that the polymer has a lower average molecular weight or that it has a high molecular weight but is highly branched.

Since friction reduction is a function of polymer linearity, any change which alters the conformation (effective length-to-width ratio) of the polymer can often be detected in the turbulent-flow rheometer. Figure 16 shows results when DNA was tested for friction-reduction effectiveness in the presence of a number of compounds believed to alter molecular conformation (Ref. 20). The dyes 9-amino acridine and proflavine showed large increases in friction reduction when mixed with DNA. These materials are believed to interact strongly in the DNA helix, extending the length of the molecule. Repeated frictional tests showed that these materials also greatly strengthen the DNA to shear degradation. Actinomycin-D also exhibits the same characteristics with DNA, although the binding may not involve the same type of interaction as with the dyes. In contrast, acridine orange seems to interact to such an extent as to separate the DNA helix components so that its friction reduction was practically identical to that of a DNA preparation which had been denatured by bringing a water solution to 90°C and rapidly cooling it. Tests with the carcinogens 3, 4-benzpyrene and 1, 2, 5, 6-dibenzanthracene and the near carcinogen, phenanthrene, indicated some lowering of the friction-reduction effect (Fig. 17). This may be due to the partial unwinding of a helix or at least to a weakening which allows mechanical shear to partially separate the helix pairs (Ref. 20).

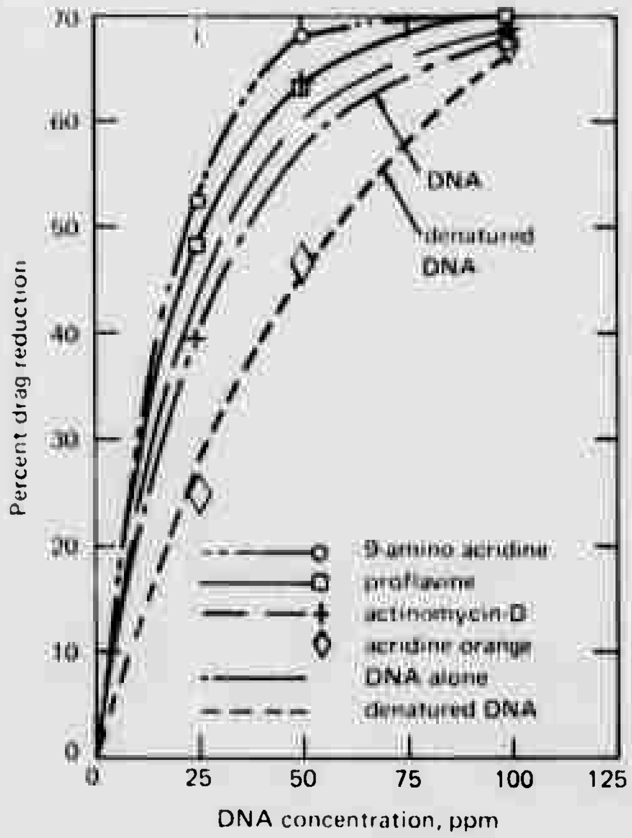

Figure 16. Friction-reduction measurements of DNA, denatured DNA, and DNA with acridine dyes and an antibiotic as a function of DNA concentration.

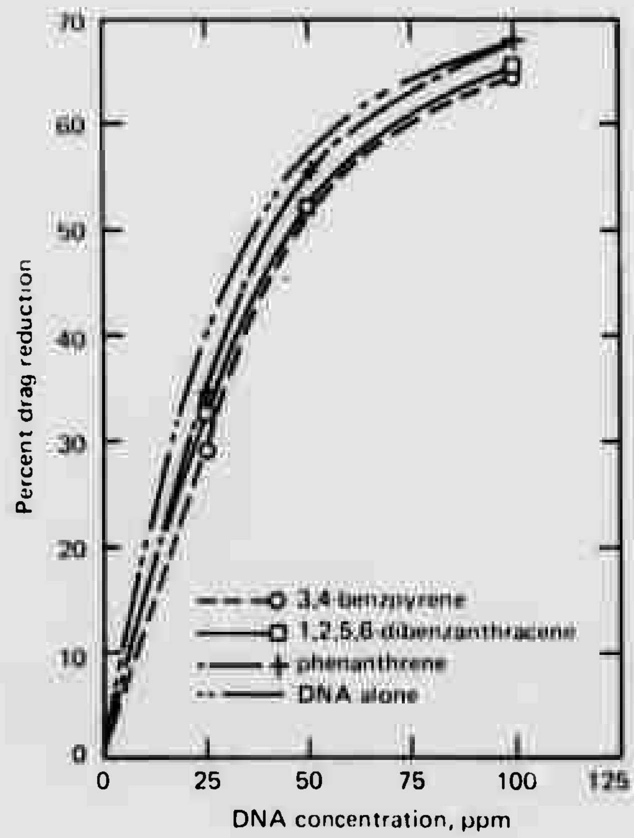

Figure 17. Drag-reduction measurements of DNA and DNA with carcinogens and a hydrocarbon as a function of DNA concentration.

More insight may be gained into the physical chemistry of long-chain polymers by utilizing friction reduction versus concentration curves combined with friction reduction versus shear curves. Shear degradation curves are easily obtainable by repeatedly passing the same solution through the fine bore tube of the turbulent-flow rheometer and measuring the friction-reduction effectiveness during each pass. Friction reduction versus concentration plots can be used to rapidly estimate molecular weights of long-chain polymers when reference polymers of known molecular weight are available (Ref. 18). This information combined with hydrodynamic degradation and other data may help reveal the nature of bonding, molecular interactions, and molecular weight distributions in solutions of long-chain polymers.

Figure 18 shows the friction-reduction effectiveness of several bacterial polysaccharides and guar gum after increased exposure to turbulent flow (Ref. 14).

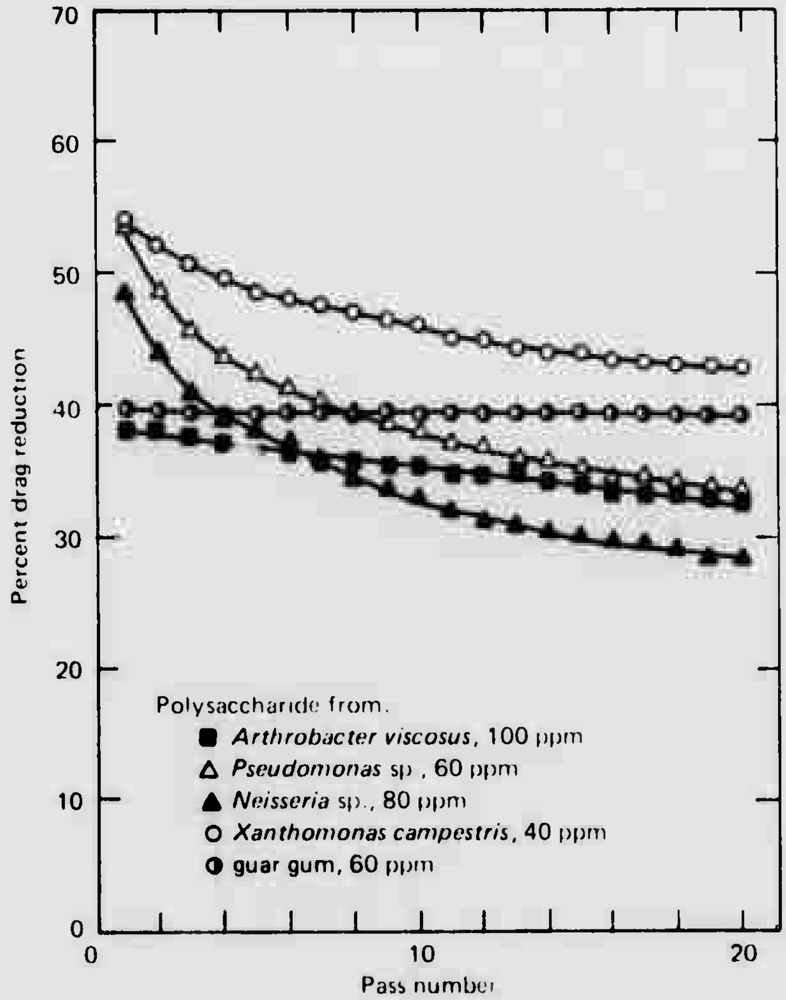

Figure 18. Drag-reduction effectiveness of bacterial polysaccharides and guar gum after repeated passes through the turbulent-flow rheometer.

Guar gum was influenced the least, showing little loss in friction-reduction effectiveness after 20 passes through the fine bore tube of the rheometer. Bacterial polysaccharide from *Arthrobacter viscosus* showed slightly less stability. Bacterial polysaccharide from *Xanthomonas campestris*, *Pseudomonas* sp., and *Neisseria* sp. showed an initial decrease in friction-reduction ability after the first several passes through the tube and less of a change after subsequent passes. This initial decrease in friction reduction is probably due to the greater fragility of the longer polymer chain: the increased stability after subsequent passes is probably due to the more stable, shorter chains.

It is interesting that polysaccharide from *A. viscosus* was apparently degraded more than guar gum, and that polysaccharide from *Pseudomonas* sp. and *Neisseria* sp. was more degraded than polysaccharide from *X. campestris*. The greater friction-reduction ability of guar gum and polysaccharide from *X. campestris* suggests that guar gum is a longer molecule than polysaccharide from *A. viscosus* and that polysaccharide from *X. compestris* is longer than polysaccharides from *Pseudomonas* sp. and *Neisseria* sp. The longer polymer chains would be expected to be more sensitive to turbulent-flow degradation. Their increased stability, however, may be due to stronger bonds between monomeric units or to decreased stresses placed on these bonds as a result of intramolecular and intermolecular interactions. This anomaly may also reflect different molecular weight distributions.

Other applications of the turbulent-flow rheometer include the measurement of polymerization and depolymerization reactions which involve long-chain polymers and the measurement of the production of extracellular polysaccharides by microorganisms. As shown previously, extracellular polysaccharide production is readily demonstrated by testing the culture for friction-reduction effectiveness (Fig. 3 to 6). Finally, it should be noted that the friction-reduction measurement is particularly valuable in that polymer concentrations can be detected far below those discernable by viscometry when a linear polymer is involved.

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13. ABSTRACT

Long-chain polymers from many seaweeds, microscopic algae, and bacteria have been demonstrated to reduce turbulent-flow friction in water. In this investigation all water samples tested from inland and marine sources gained friction-reduction ability when enriched with sugar, as a consequence of polysaccharide synthesis by bacteria. Biological polymers, therefore, are the probable cause of the unexplainable variations in hydrodynamic test facilities. Bacterial polysaccharides were more effective than seaweed extracts at low concentrations for friction reduction, but both were much less effective than synthetic polymers. Turbulent-flow frictional measurements were found to be sensitive for the detection, measurement, and partial characterization of long-chain polymers.

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