Experimental Model Studies of Non-Newtonian Soluble Coatings for Drag Reduction

S. THURSTON* AND R. D. JONES†
Northrop Corporation, Hawthorne, Calif.

A soluble coating has been developed which can be applied to the surface of an underwater body, with a resulting reduction in friction drag. The coating dissolves in a predictable manner so that the body rides in a boundary layer of non-Newtonian fluid. A model test program was carried out in a simple drop-tank facility, using a small body of revolution. The distance-time relationship was accurately measured and the drag derived therefrom. Tests were made in both fresh water and sea water with very promising results, although the tests were not systematic and the location of the coating was limited to the stagnation region of the nose. Reductions in total model drag of 18% with fresh water and 16% with sea water were obtained which corresponded to reductions in model friction drag of 30 and 27%, respectively.

Background

THE U. S. Navy and Merchant Marine require continual improvement in the performance of their surface ships and undersea craft in order to retain a favorable and competitive position on the international scene. Unfortunately, in past years, research in marine systems has been severely neglected, and advances in the state of the art have been very modest or nonexistent. However, specific needs have been identified and research and development recently has been stimulated to focus on the most critical problems. Programs are being pursued to increase the efficiency of propulsion systems and powerplants and to reduce wave drag and friction drag. However, for all practical considerations, because the friction drag of any marine craft increases exponentially with velocity, friction drag represents the major barrier limiting the attainment of higher speeds and major performance improvements. Development of concepts and techniques for penetration of this drag barrier represents the next major formidable challenge confronting designers of advanced marine systems.

If a body moves through a perfect fluid or through a vacuum, there is no drag. As a result, energy is not required to keep the body in motion once it is started. However, in real fluids, such as water or air, the viscosity effects and fluid reaction with the body cause a friction drag force. The friction drag is the result of the shear forces existing between adjacent fluid laminae, or streamlines adjacent to the body, caused by the influence of the body surface. The total region within which shear forces act is designated as the boundary layer.

The flow region over the body, within which shear forces act, can be either laminar or turbulent in nature. For most practical body shapes, the flow is laminar at the leading edge region of the body and then goes through a transition zone to become turbulent as it progresses downstream. A comparison of the growth of typical laminar and turbulent boundary layers on a flat plate and the corresponding local velocity profiles are shown in Figs. 1 and 2. A laminar boundary layer results in substantially less friction drag than a turbulent boundary layer.

Since the development of successful drag reduction techniques will greatly improve the performance of marine systems, attention is being given to a variety of approaches, e.g., methods of delaying transition from laminar to turbulent boundary layers. These include 1) use of suction to stabilize the boundary layer; various mechanical techniques are being considered, including the use of various configurations of slots and/or porous walls; 2) control of body shape; and 3) use of flexible coatings that are sensitive to local pressure.

Other approaches include 1) injection of water, gas, and/or air films between the body and the fluid; 2) acoustic excitation of the flow to change the nature of the boundary layer; and 3) generation of non-Newtonian fluid properties by the addition of additives. These approaches involve both the injection of solutions of additives into the boundary-layer region and the use of soluble coatings located on the body surface.

Although all of the forementioned schemes are theoretically feasible and have been known for many years, considerable research and development is needed before they can be put into practice and used with confidence. Also, some of the schemes may be better than others for specific applications and missions.

Non-Newtonian Additives

The use of non-Newtonian additives or coatings represents a very interesting approach for reducing drag, especially for missions of short duration. Although the general characteristics of non-Newtonian fluids have been known for many years, they have been recognized only recently as possible candidates for drag reduction.[1–5]

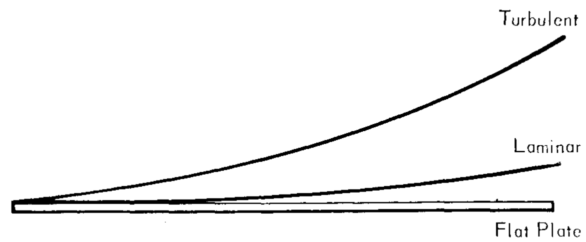

Fig. 1 Growth of typical laminar and turbulent boundary layer on flat plate.

Presented as Preprint 64-466 at the 1st AIAA Annual Meeting, Washington, D. C., June 29–July 2, 1964; revision received November 16, 1964. The subject program was conducted while the authors were employed by Astropower, Inc., a subsidiary of the Douglas Aircraft Company. The authors gratefully acknowledge the work of Levy-Pascal and Byrd of Astropower, Inc., who evolved the chemical formulations of the coatings and contributed much valuable information during the subject program.

* Chief, Advanced Underwater Systems, Norair Division. Member AIAA.

† Senior Engineer, Nortronics Division. Member AIAA.

The mechanism of non-Newtonian fluid flow is not completely understood at present, and is the subject of considerable research. However, an insight into the behavior of a non-Newtonian fluid can be acquired by comparing it with water. In a fluid such as water, the shear stress is proportional to the rate of shearing deformation adjacent to the body surface; this ratio is a constant of proportionality. The constant of proportionality is the coefficient of viscosity, and the water is said to exhibit Newtonian behavior. The shear stress at the body surface is

$$\tau_s = \mu(du/dy)_s$$

where μ = the absolute coefficient of viscosity, and $(du/dy)_s$ = velocity gradient (rate of shear) at the body surface.

Typical fluids, other than water, which exhibit Newtonian behavior are oils, varnishes, syrups, and petroleum products. However, there are fluids in nature (classed as non-Newtonian fluids) for which the ratio of the shear stress to the rate of shear is no longer constant. Examples of this type of fluid are colloids, emulsions, polymer suspensions, and some organic materials.

The behavior of non-Newtonian fluids can be illustrated by examining the flow of various fluids through a capillary tube. Figure 3 shows typical relationships of the flow velocity in a capillary tube as a function of pressure loss across the tube for various general classes of non-Newtonian and Newtonian fluids.

Newtonian fluids exhibit linearity between velocity and pressure loss, whereas non-Newtonian fluids exhibit substantial deviation from linearity, depending on the nature of the particular liquid. The flow of a non-Newtonian fluid over a body also would be considerably different from that of a Newtonian fluid.

A detailed theory of drag reduction with non-Newtonian additives can only be hypothesized at the present time. It has been suggested that the use of such additives delays the transition from laminar to turbulent flow and reduces turbulence and the resulting kinetic energy losses, influences separation, or perhaps reduces the viscosity or interfacial tension due to the rheological action of the fluid. Other considerations involve modification of the basic flow curve and velocity profile within the boundary layer. There is insufficient experimental data to establish any single definitive flow mechanism. The flow behavior appears to be very complex and may be a combination of various phenomena. Paradoxically, some of the materials that have been used successfully are known to increase the viscosity in certain concentrations. Also, there is evidence that the drag reduction is not related to transition phenomena and not necessarily limited to the drag reduction attainable with laminar flow. It is logical to conclude that additives can be used with purely laminar flow to reduce friction drag further. Research is necessary in order to obtain an understanding of the actions of the additives.

A number of chemicals have been identified by the Naval Ordnance Test Station (NOTS)[1] which act to reduce substantially the friction drag of water flowing in pipes when added in very small quantities. These chemicals are related insofar as they are polymers with a high molecular weight and a long-chain molecular structure. Some of the more promising chemicals are Guar (J-2FP), Colloid HV-6 (refined Guar), and Polyox WSR-301.‡

It is of interest, as noted in Ref. 1, that even some living materials in solution reduce friction drag; examples of these are slime scraped from sea fish and from the sea snail.

A soluble coating has been developed by Astropower, Inc., which can be applied to the surface of an underwater body with a resulting reduction in friction drag. This coating dissolves in a predictable manner so that the body rides in a boundary layer of non-Newtonian fluid. Model tests of a simple body of revolution with the coating has demonstrated a reduction in friction drag of over 30% with fresh water and 27% with sea water. The results of the experimental program are presented below.

‡ The chemical composition and formulation of these coatings are proprietary to Astropower, Inc., a subsidiary of the Douglas Aircraft Company.

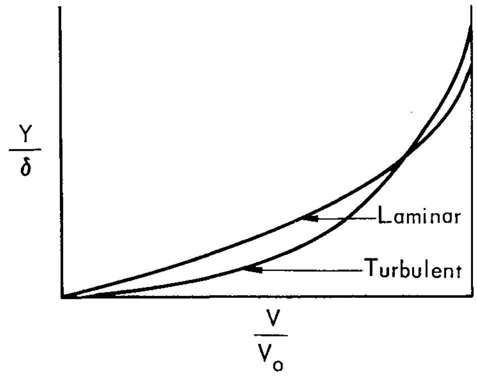

Fig. 2 Comparison of typical laminar and turbulent boundary-layer profiles.

Test Configuration and Procedures

Model Tank

The experimental work was carried out in the model test tank shown in Fig. 4. Selection of this tank, 2 ft in diameter and 20 ft long with a capacity of approximately 500 gal, was based primarily on low cost and ease of fabrication. In addition, the tank was amenable to rapid changes of water, to eliminate the possibility of contamination, even by small amounts of the chemicals. The tank is shown schematically in Fig. 5.

The tank was instrumented at nine vertical stations, located 2 ft apart, to determine the distance-time relationship. At each station, a 150-w floodlight was directed to project a plane of light through a horizontal slit 0.06 in. wide by 3 in. long. Light sensitive resistors were mounted at each end of the light slit to register the nearly instantaneous change in light intensity due to the reflectivity of the model as it passed the plane of light. The models were painted black, with the exception of a reflective ring around the center section, to re-

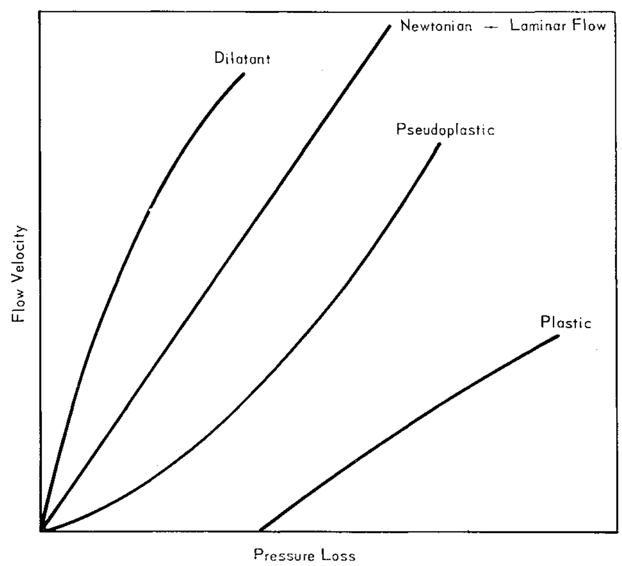

Fig. 3 Variation of pressure loss in capillary tubes with flow velocity for various non-Newtonian fluids.

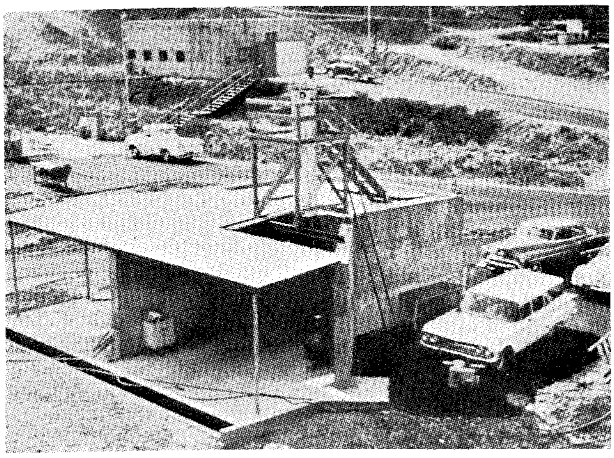

Fig. 4 Test tank.

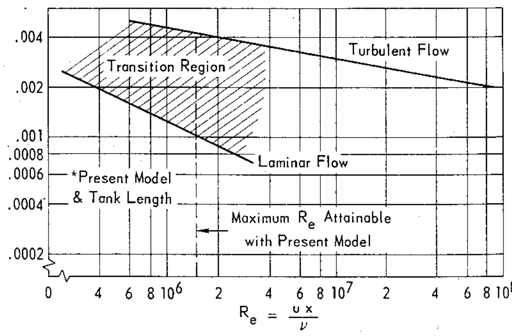

Fig. 6 Flat plate skin-friction coefficient as a function of Reynolds number.

flect light from the source back to the light sensitive resistors. The output of the resistors was recorded as a function of time on an oscillograph recorder.

An electromagnetic release mechanism for the model was located at the top of the tank. In addition to the trajectory information, the temperature and kinematic viscosity was determined before and after each test.

The range of Reynolds numbers attainable with the model test tank and their relationship to the transitional and turbulent regions is shown in Fig. 6. A maximum Reynolds number of 1.2×10^6 was attained. It would be desirable, as a logical next step, to extend the tests to higher Reynolds numbers by the use of a longer tank and larger models.

The basic model is shown in Figs. 7 and 8. Two basic interchangeable nose shapes were used: a blunt nose and a streamlined nose. The blunt nose assured the attainment of turbulent flow and a high erosion rate of the coatings, and the streamlined nose was selected so that laminar flow would result over a large portion of the body. However, the initial program was concerned primarily with the turbulent regime, and only a few tests were made with the streamlined nose.

In view of the relatively small diameter of the tank, it was necessary to minimize dispersions in the vertical trajectory. The model, therefore, utilized four relatively large tail fins canted at 5° to the centerline to produce a control-clockwise spin of approximately 1 rev/sec. This corresponded to approximately 2 rev for a complete trajectory. High-speed motion pictures made of a typical test verified that a high degree of stability was inherent and that there was virtually no dispersion in the trajectory.

To insure uniformity of test results and to make certain that the water did not become contaminated with chemicals and obscure the actual effects, each series of tests was preceded by and then followed by three tests utilizing an uncoated blunt nose. This configuration was used as a standard for evaluating the instrumentation and the conditions of the water. If any deviation from the known drag occurred, the tank water was changed before proceeding further.

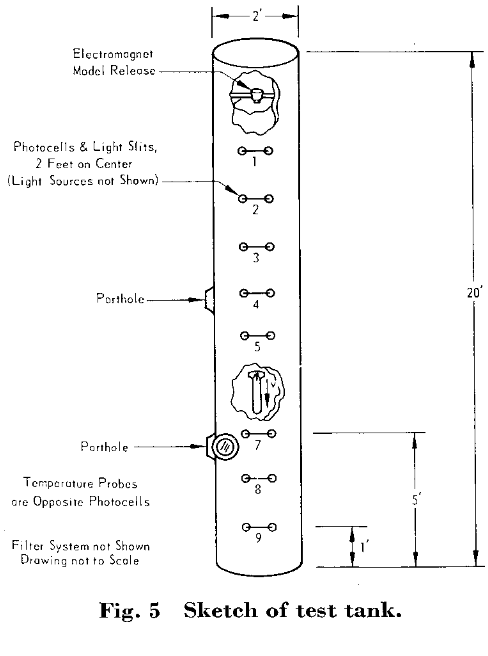

Fig. 5 Sketch of test tank.

Location of Coating

The establishment of the location on the body for placement of the non-Newtonian additive or coatings is important. Because of the lack of understanding of the mechanism of the flow, the location is subject to speculation and intuitive reasoning. The present tests were carried out with the location restricted to the forward stagnation region of the body. This selection was based on qualitative considerations of boundary-layer behavior. After the initial tests, it was intended to extend the tests to include other locations on the body. The coatings can be distributed over a wide area or over the entire body, if required, to attain the optimum results.

The reason for locating the coating in the forward stagnation region of the body for the initial tests was largely intuitive; the boundary layer thickens as the flow progresses aft from the leading edge of the body. The fluid particles that comprise the boundary layer are, for all practical purposes, contained by the bounding streamline as the flow progresses downstream. This is illustrated in Fig. 1 for a flat plate. By treating the fluid particles with chemical additives to change their properties in the forward stagnation region, all the fluid in the boundary layer region will be acted upon.

It was recognized that there would be practical limitations imposed by the foregoing approach. As the major portion of the mass flow is concentrated in the outermost sections of

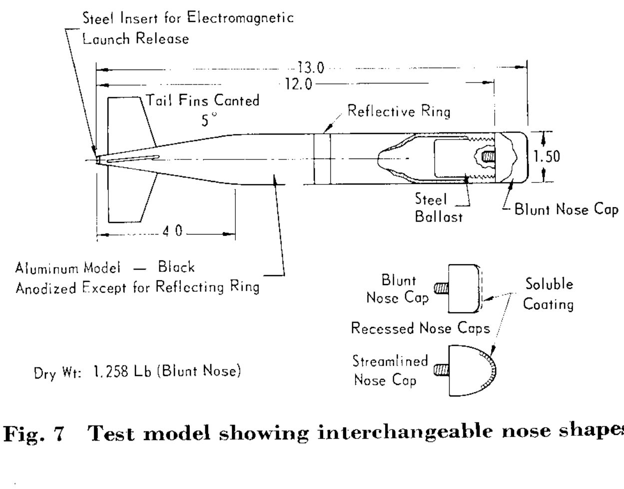

Fig. 7 Test model showing interchangeable nose shapes.

the boundary layer, complete and uniform mixing of the additive with the flow is not to be expected. The concentration is expected to vary throughout the boundary-layer region. In addition, some portion of the flow treated with the additive would be lost from the boundary-layer region as a result of momentum transport and mixing. Therefore, downstream locations for the coating may be desirable for optimum results.

Accuracy of Test Results

Since evaluation of the accuracy of the test data is an important part of an experimental program, the instrumentation and data were examined thoroughly to verify meaningful results.

The test tank was instrumented for measurement of the position-time history of the model as it followed its vertical trajectory. The velocity was determined as an average velocity

$$\left(\bar{V} = \frac{\text{the distance between light slits}}{\text{time to travel this distance}}\right)$$

between any two measuring stations. The acceleration then is an average acceleration derived from the velocity-time relationship. Some typical plots showing the experimentally measured distance-time relationships and the derived velocity and acceleration curves are shown in Fig. 9. The model approaches its terminal velocity very near the end of its run; at this time the acceleration is nearly zero.

A detailed error analysis was carried out to evaluate the accuracy of the data. The error analysis covered the range of anticipated performance conditions and test parameters. The maximum absolute error in time measurement is 2 msec. The time to travel the 2-ft increment between measuring stations at a terminal velocity of approximately 13 fps is approximately 0.16 sec, which results in an error of 1.3%. The corresponding maximum error in the drag, based on terminal conditions, is estimated to be approximately 2 to 2.5%.

There are a number of additional factors that influence accuracy and repeatability of test results. These include variation in the coating thickness, the surface roughness of the coating, and the slight variation in shape due to erosion. In addition, as the tests were carried out during hot weather, some vertical temperature gradients were present. However, considering all factors, it is estimated that the measured drag coefficient did not vary more than ±5%. The data at the higher Reynolds number, when terminal conditions are approached, are the most accurate and should be used for evaluating the coating effectiveness.

Experimental Results

The goals of the model test program were to demonstrate the feasibility and effectiveness of using soluble coatings to reduce drag. Although the tests were not completely systematic and a number of performance aspects are still to be explored, the feasibility was firmly established on a model scale. The results are sufficiently encouraging to recommend an accelerated program and extension to larger-scale tests. Reductions in total model drag of 18% with fresh water and 16% with sea water were obtained which corresponded to reductions in model friction drag of 30 and 27%, respectively.

A summary of the pertinent results of the fresh-water tests is shown in Fig. 10. Each curve represents the average of three to six test runs. The ordinate represents the percentage decrease in total measured drag of the model with the coating, compared to the uncoated model, whereas the abscissa is the Reynolds number. Each curve defines a complete trajectory, with the lowest Reynolds number attained immediately after the model is dropped. A reduction in the measured model drag of approximately 18% was obtained, and the results were, for the most part, constant over almost the entire trajectory, except for the initial period. A maximum Reynolds number of approximately 1.2×10^6 was attained at the end of the trajectory, and closely represented terminal conditions.

The basic chemical formulation of the coating is approximately the same for all the tests. However, there was a preliminary attempt to explore the effects of mixture ratio by varying the proportions of the chemicals used over a limited

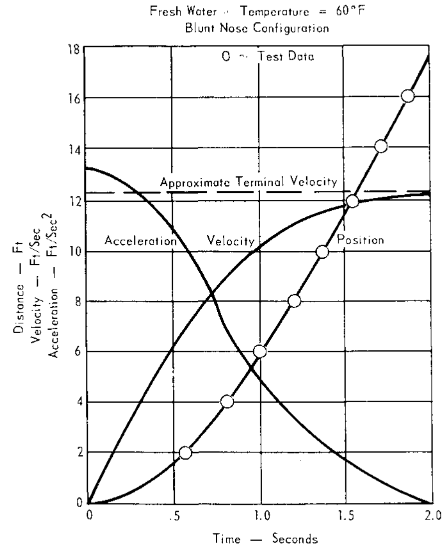

Fig. 9 Typical results of model tests.

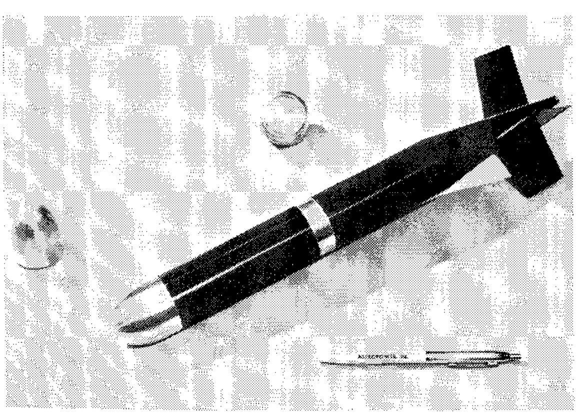

Fig. 8 Test model showing interchangeable nose shapes.

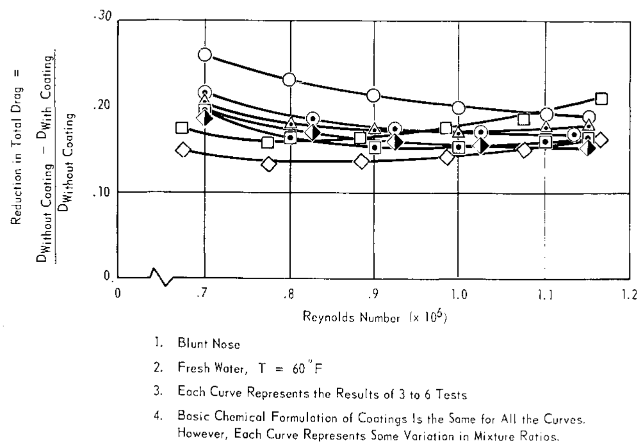

Fig. 10 Reduction in total drag by using soluble coatings from model tests in fresh water.

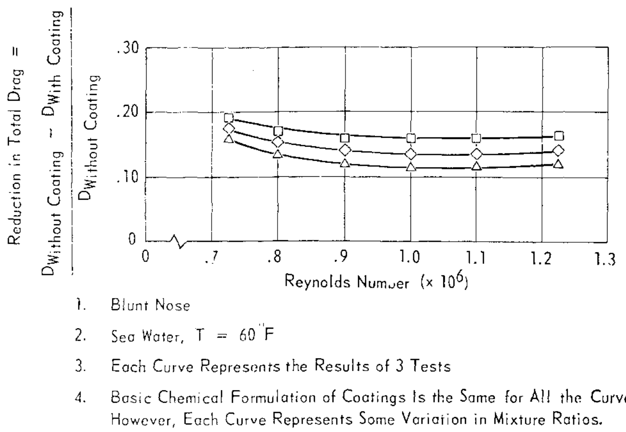

Fig. 11 Reduction in total drag by using soluble coatings from model tests in sea water.

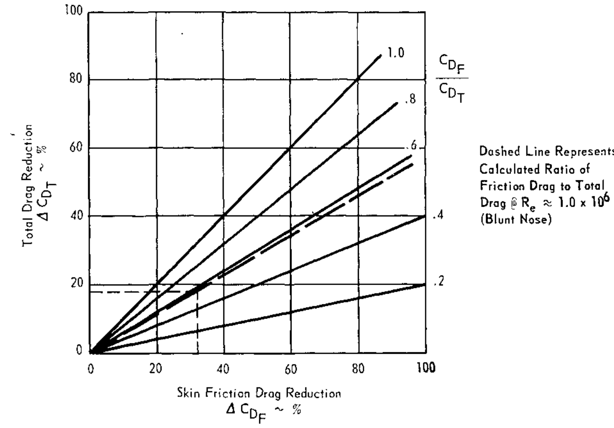

Fig. 12 Variation of total drag reduction with skin-friction drag reduction.

range. The results did not show any specific, well-defined effect. There was no systematic attempt to include erosion rate as a parameter at this time, although it is related to mixture ratio. More systematic tests of an exploratory nature are desirable to determine in detail the effects of various chemical formulations and erosion rates.

Some of the tests were repeated using sea water and the results are shown in Fig. 11. In general, the results are similar to the fresh-water results and the total drag of the model was reduced by approximately 16%. In all aspects, the coatings appeared to act similarly in both fresh water and sea water, although the drag reduction in sea water was a little less. Also, a trend in the variation in mixture ratio of the coating chemicals appears to be emerging but is not well defined. Unfortunately, the number of sea-water tests was very limited and additional testing is needed to obtain significant quantitative results.

The previous discussions concerned the measured reduction in the total drag of the model caused by the coating. However, it is of interest to explore further the details of this reduction in total drag and to evaluate the component of drag which is most affected. Pipe flow and rotating disk tests[1] demonstrate conclusively that non-Newtonian additives act to reduce substantially the friction drag of water flowing over surfaces. It is reasonable to expect that the additives act in a similar manner for external flow over a body, although it is realized that changes in friction drag can also cause changes in the separation point and form drag. However, it appears that these are of secondary importance. Therefore, it is significant to explore the relationship of skin friction to the total drag of the test model. To do so, a graphical presentation of total drag reduction as a function of skin-friction drag reduction was prepared for various ratios of friction to total drag (refer to Fig. 12). Design calculations show that in the present model the ratio of friction-to-total drag is approximately 0.59, which is displayed as a dashed line. This low value results from the high form drag and induced drag contributions for the model. The 18% reduction in total drag, which was experimentally obtained during the fresh-water tests, therefore corresponds to a reduction of approximately 30% in body skin-friction drag. The 16% reduction in total drag obtained during the sea-water tests corresponds to a reduction of approximately 27% in body skin-friction drag.

Some tests also were conducted utilizing the streamlined-nose section, in which laminar flow is expected over a large portion of the body. The basic configuration demonstrated a 30 to 40% lower total drag than the blunt-nose configuration without coatings, indicating laminar flow over a substantial region of the body. A portion of the nose was coated and some tests were made; however, a reduction of drag was not measured. It was suspected that the erosion rate was insufficient to attain the needed concentration of chemicals in solution because of the relatively small region coated and the low mixing rate within the laminar boundary layer. Increasing the erosion rate by spreading the coating over a wider area of the body was considered but was not carried out because of a primary emphasis on the turbulent case. It is anticipated that, with proper control of the coating and related parameters, a reduction in drag could be attained with either laminar or turbulent flow. This premise is the subject of further research and investigation.

Conclusions

The results of the experimental studies clearly demonstrate the feasibility of using a soluble coating material to reduce drag of an underwater body. In essence, a body so treated rides in a boundary layer of non-Newtonian fluid, a phenomenon of direct interest for increasing the range and speed of many types of vehicles which operate in water and have missions of short duration.

Further research assuredly will provide a basis for a more complete understanding of the mechanism of non-Newtonian flow and the actions of additives and coatings, and will lead to even greater improvements than those presented in this article. However, the results obtained thus far are sufficient to merit serious consideration of soluble materials of this type, even at this early developmental stage.

References

[1] Hoyt, J. W. and Fabula, A. G., "The effect of additives on fluid friction," Fifth Symposium on Naval Hydrodynamics, Bergen, Norway (September 1964).

[2] Ripken, J. F. and Pilch, M., "Studies of the reduction of pipe friction with the non-Newtonian additive CMC," St. Anthony Falls Hydraulic Lab. Tech. Paper 421, Ser. B (April 1963).

[3] Granville, P. S., "The frictional resistance and boundary layer of flat plates in non-Newtonian fluids," J. Ship Res. **6**, 43 (October 1962).

[4] Dodge, D. W. and Metzner, A. B., "Turbulent flow of non-Newtonian solids," J. Am. Inst. Chem. Engrs. **5**, 109–204 (June 1959).

[5] Wilkinson, W. L., *Non-Newtonian Fluids* (Pergamon Press, New York, 1960).