Effect of Polymer Additives on Propeller Performance

T. Kowalski*
University of Rhode Island, Kingston, R.I.

Recent experiments with the drag reducing polymer additives suggest their possible application as a means of reducing skin-friction component of the total ship's resistance. Since most of the ships are propelled by a screw located at the stern, a question arose as to the effect of the friction reducing additives on the performance of the propeller passing through the polymer solution remaining in the wake of the hull. Open-water tests were performed with a model propeller in a water flume with polymer injection ahead of the propeller disk. The thrust and torque were measured at a number of revolutions and at one rate of flow of water. The analysis of the tests indicates a definite reduction of propeller thrust and an increase of torque when polymer additives were injected ahead of the propeller disk, resulting in the reduction of the propeller efficiency "in the open." For an average concentration of 20 ppm of the additive passing through the propeller disk, the efficiency was reduced by approximately 5%. The over-all experimental procedures were checked by replacing the propeller by a thin disk and the usual reduction of torque was obtained. A possible explanation of the reduction of the propeller efficiency is suggested based on the change in the geometry of the propeller blades because of the adsorption of polymer to the leading edges of the blades and a general thickening of the blade profiles. Finally, tests are proposed to determine the effect of polymer additives on the lift and drag of basic hydrofoil sections in an effort to explain the reductions in propeller performance.

Introduction

THE drag reduction phenomenon of certain long chain polymers has been known for some considerable time. A great amount of research has been conducted to investigate the extent and the underlying principles of the drag reduction in internal flows such as flow through pipes. Comparatively little research effort has been expended in the investigations of the drag reducing phenomena in the more difficult area of external flows. The reason for investigating the external flows lies in the possibility of utilizing the drag reducing effect of the polymer additives in bodies moving through water. In these cases, the additive is injected into the boundary layer of the body and an attempt is made to retain the polymer inside the boundary layer throughout the length of the submerged part of the body. Since most of the ships are propelled by a screw located at the stern, a question arises as to the effect on the performance of the propeller as some of the additive flows through the propeller disk. The same problem occurs in the case of pump impellers if the polymer is added ahead of the pump to influence cavitation, noise, and separation in the diffuser.

Experiments were conducted to determine the effect on the propeller performance of the presence of drag reducing additives. These experiments were a part of a larger research into the reduction of drag in ships. Preliminary results were reported to the 15th American Towing Tank Conference, Ottawa, June 1968. Because of the considerable interest in these unexpected results the tests were extended and performed a number of times to confirm their repeatability.

Description of Apparatus and Test Procedures

The tests were performed in a large recirculating open channel 18-in. × 18-in. × 40-ft length. The channel was modified to permit dumping of contaminated water when the polymer was being added.

The model propeller had the following characteristics: number of blades, 3; diameter, 4.67 in.; pitch ratio, 0.786; Boss diam ratio, 0.1714; maximum thickness ratio, 0.0468; projection area ratio, 0.480; developed area ratio, 0.550; airfoil and circular back sections with skewback and rake; constant pitch. The propeller was driven by a $\frac{1}{4}$-hp electric motor through a hydraulic reduction device.

Two types of test equipment were used: 1) A right angle drive is shown in Fig. 1. This consisted of the propeller mounted on a horizontal shaft facing forward (propeller in the open) and the motor with the reduction box mounted on a vertical shaft. The whole assembly was mounted on a floating frame suspended by four flat springs from a fixed frame attached to the sides of the flume. A linear variable dif-

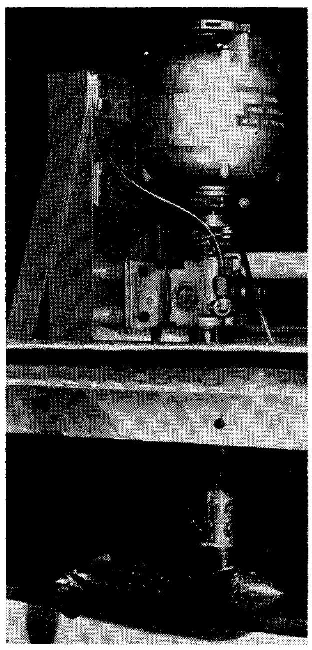

Fig. 1 Thrust balance.

Received August 5, 1970. The research described in this paper was made possible by a grant from the Defence Research Board of Canada (Research Grant No. 9550-28). The author is also indebted to S. T. Mathews, Head, Ship Model Tank, National Research Council of Canada for the loan of the Thrust and Torque balance and the model propeller.

* Associate Professor, Department of Ocean Engineering.

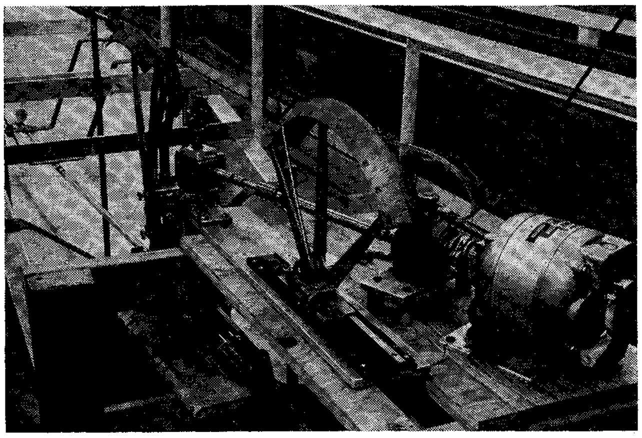

Fig. 2 Thrust and torque balance.

ferential transformer was used to measure the relative deflection between the floating and the fixed frames due to the drag of the water on the immersed part of the apparatus and due to the propeller action. The vertical and horizontal shafts were housed inside streamlined support members. This equipment could measure horizontal forces only i.e., drag of the apparatus and the thrust of the propeller. 2) A thrust and torque dynamometer were manufactured by Kempf and Remmers (see Fig. 2). The same electric motor and reduction device were used to power the dynamometer which was located at the end of the flume with the propeller well within the flume itself (Fig. 3). The thrust of the propeller was balanced by a spring and weight with the fine reading given by a deflection of a pointer. The torque was balanced by the torsion of a spring and the remainder read from a deflection of a pointer. The dynamometer was purely a mechanical device without any electronics.

The injection was accomplished by feeding the polymer from a container under constant air pressure into three aluminum tubes of $\frac{1}{4}$-in. i.d. The tubes were located on the centerline of the flume 4 ft ahead of the propeller; the square ends of the tubes 1 in. apart vertically and centered between the surface of the water and the bottom of the flume. This arrangement produced the most uniform inflow of the polymer additive into the propeller disk (checked by dye injection tests).

The velocity of the water in the flume was measured by means of a freely rotating vane device which gave number of revolutions over a measured length of time. Using calibration charts the revolutions/sec were converted to velocity of water in fps.

The tests were run at one velocity of water in the flume (approximately 3 fps) and a number of revolutions of the propeller from 1000 rpm to 1600 rpm. At a given rpm of the propeller, the thrust and torque in the water were read then the polymer was injected at a rate to give an average concentration of the additive at the propeller disk of 20 and 40 ppm and the thrust and torque were again read from the dynamometer. A check was also made of the revolutions of the propeller and the velocity of water in the flume while polymer was injected.

The results are given in terms of nondimensional coefficients of thrust and torque to the base of the advance coefficient as defined below:

$$K_T = \text{thrust}/\rho n^2 D^4;\ K_Q = \text{torque}/\rho n^2 D^4;\ J = V_0/nD;$$
$$\eta = (J/2\pi)K_T/K_Q$$

where n = propeller revolutions in revolutions/sec, D = propeller diameter in ft, V_0 = velocity of water into the propeller disk in fps, ρ = density of water in slugs/ft^3, η = propeller efficiency "in the open." Another important consideration during the tests was the method of preparation of the polymer additive. Polymer used was Union Carbide's Polyox FRA of approximate molecular weight of 6×10^6 an additive widely researched and proven as a drag reducing agent. The mixing of the polymer in tap water was performed under identical conditions as far as possible. The powder was sprinkled one layer thick on top of water in large trays. As soon as the first layer became saturated with water and began to sink to the bottom another layer was sprinkled on the top. This was continued until all the powder was used. The solution was not stirred or agitated until the last layer of powder was completely wetted. This procedure took two days and then the solution was poured into plastic buckets and poured gently from one bucket to another a few times until the solution was uniform to the eye. At the beginning the solution contained visible clumps and thick threadlike aggregates of polymer which disappeared during final mixing. A $\frac{1}{2}\%$ by weight concentration was always made and on the third day was thinned to $\frac{1}{4}\%$ and used in the experiments. Any unused solution was thrown away.

The spread of the injected polymer solution was observed using dyed samples. The dye used was Rhodamine B, an excellent vegetable base substance checked in drag reducing tests not to degrade Polyox type of polymers.

To check the drag reducing effect of polymer additives used in the experiments a test was performed on a thin disk mounted in place of the propeller. The disk was $\frac{1}{8}$ in. thick and of the same diameter as the propeller. Drag and torque measurements were taken at the same water flow velocity with and without the additive for the same range of revolutions as the experiments with model propeller.

Test Results and Discussion

The first set of tests was performed using the floating frame thrust dynamometer. Measurements of propeller thrust were obtained at four revolutions of model propeller in water and in water with polymer injection resulting in an average concentration of the additive at the propeller disk of 20 ppm. Two additional runs were made at twice the injection rate of polymer additive giving a 40-ppm concentration at the propeller. The results are given in Table 1 and Fig. 4. They show an almost constant reduction of thrust coefficient throughout the speed of advance range when polymer was added. The reduction amounts to approximately 7% for 20-ppm concentration of polymer and 14% for 40-ppm concentration. Since the thrust coefficient varies inversely with (revolution)^2 the parallel behavior of thrust coefficient curves implies that the polymer effect is dependent on the revolutions within the operating range of the propeller model.

The somewhat unexpected thrust reduction observed in the previous tests prompted a much more detailed study of the effect of the polymer additives on propeller performance. A second set of tests was therefore conducted on the same propeller under the same polymer injection conditions but

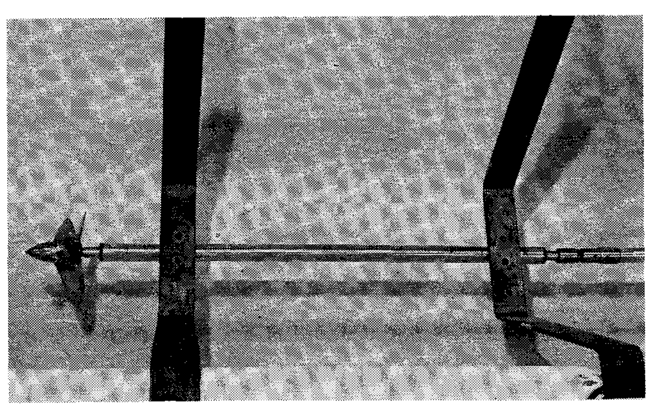

Fig. 3 Location of the propeller in the flume.

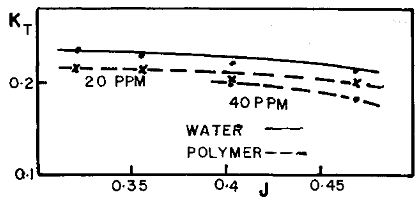

Fig. 4 Propeller thrust results.

using a different dynamometer capable of measuring torque in addition to propeller thrust. Two separate sets of experiments were performed on two occasions one month apart but covering the same range of parameters. The results are given in Tables 2 and 3 and are drawn in Figs. 5 and 6. In addition to thrust and torque coefficients propeller efficiencies are also given showing the over-all effect of the additives on the performance characteristics of the propeller model.

The results show quite clearly the reduction of propeller thrust and increase in torque absorbed by the propeller resulting in the over-all reduction of the propeller efficiency of about 5%.

The effect of the polymer additives on the propeller characteristics is difficult to explain at present. More basic type of investigations will have to be performed in an effort to understand the action of the polymer additives. Some possible causes are suggested.

The presence of polymer additives in the flow increases the displacement thickness of the boundary layer of the propeller blade profile affecting the camber and thickness of the sections thereby reducing the lift. This could result in the observed thrust decreases. A thicker effective section will also have higher drag requiring more input torque to bring the propeller up to the required revolutions.

It has been observed by a number of investigators Metzner and Astarita,[1] Kowalski,[2] and Little[3] that Polyox type of polymer possesses a surface seeking property which causes accumulation of the polymer at a solid surface in the flow. In the case of the rotating blades, the polymer may cling and accumulate at the leading edge of the blade and change the physical shape of the blade profile changing the lift and drag characteristics of the propeller blade. It may also produce separation of the flow from the blade near the leading edge.

A similar reduction of performance of a propeller has been observed by Wu[4] as a byproduct of some drag reduction tests. Wu noticed that flow velocity produced by a pump impeller decreased in a recirculating tunnel when polymer was added to the water. He suggested that the effect could be ascribed to lift reduction developed by the blades of the propeller. Separation of the flow from the blades was discarded as an explanation on the basis that the results indicate a gradual change of impeller output rather than a sharp discontinuous type of change of performance likely in the case of the separation.

The explanation of the effect of the polymer additives on the thrust and torque of a propeller will therefore have to be sought in the effect of polymer on the lift of air-foil-like shapes. This line of reasoning is supported by an earlier investigation of the towing tests of a model of a hydrofoil boat

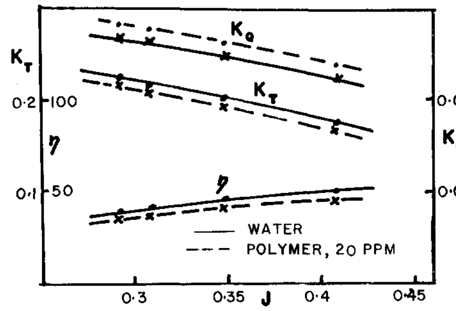

Fig. 5 Propeller thrust and torque results—September 1968.

in a towing tank performed at the U.S. Naval Academy in Annapolis by Midshipman R. Nutwell under the author's guidance. The results of the towing tests were rather disappointing as the expected reduction in the "hump" drag did not quite materialize. In retrospect it is realized that the hydrofoils may have suffered a reduction in the lift. The takeoff point occurred probably at a higher speed keeping the hull in the water a longer time resulting in a higher drag.

The tests with the thin disk mounted in place of the propeller model show a reduction both of drag and torque when additive was introduced into the flow. This confirmed that the polymer used was affecting the flow as expected. The polymer reduced the frictional resistance of the immersed surfaces, hence, the reduction of torque necessary to rotate the disk at the given revolutions; it reduced the wake of the disk

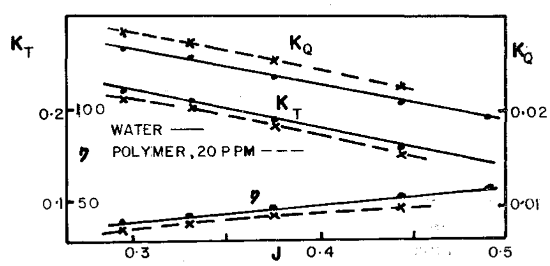

Fig. 6 Propeller thrust and torque results—October 1968.

mounted at right angle to the direction of flow hence the reduction of drag. Table 4 and Fig. 7 show the results of disk tests. Negative values of K_T indicate negative thrust which represents the drag of the nonlifting disk. Tests at zero inflow velocity showed the torque reduction which is indicative of the frictional drag reduction. This is one of the standard tests that can be performed in the towing tanks or in the laboratories to determine the drag reducing characteristics of the fluid used in the experiments.

Summary and Conclusions

Results obtained from these preliminary tests indicate a deleterious effect of polymer additives on the performance of a model propeller. The measurements show a reduction of the thrust and an increase of the torque developed by a propeller

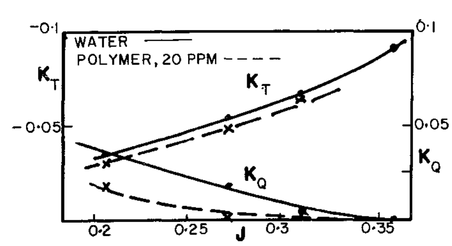

Fig. 7 Disk thrust and torque results.

Table 1 Propeller tests, June 1968

N, rpm	J	K_T Water	Polymer, 20 ppm	Polymer, 40 ppm
1000	0.469	0.215	0.200	0.181
1200	0.402	0.222	0.202	...
1400	0.354	0.228	0.213	0.200
1600	0.319	0.234	0.214	...

Table 2 Propeller tests, September 1968

N, rpm	J	K_T Water	K_T Polymer, 20 ppm	K_Q Water	K_Q Polymer, 20 ppm	η% Water	η% Polymer, 20 ppm
1000	0.408	0.175	0.167	0.0222	0.0238	51.2	45.6
1200	0.348	0.201	0.192	0.0245	0.0260	45.5	40.9
1400	0.308	0.215	0.206	0.0260	0.0274	40.5	36.8
1600	0.292	0.222	0.215	0.0264	0.0280	39.1	35.7

Table 3 Propeller tests, October 1968

N, rpm	J	K_T Water	K_T Polymer, 20 ppm	K_Q Water	K_Q Polymer, 20 ppm	η% Water	η% Polymer, 20 ppm
900	0.490	0.145	...	0.0194	...	58.4	...
1000	0.443	0.161	0.152	0.0210	0.0224	54.1	47.8
1200	0.375	0.191	0.185	0.0236	0.0250	48.3	44.2
1400	0.330	0.210	0.203	0.0254	0.0271	43.9	39.4
1600	0.294	0.221	0.211	0.0266	0.0282	38.9	35.0

Table 4 Disk tests, October 1968

N, rpm	J	K_T Water	K_T Polymer, 20 ppm	K_Q Water	K_Q Polymer, 20 ppm
1200	0.362	−0.090	...	0.0000	...
1400	0.311	−0.066	−0.0624	0.0005	0.0002
1600	0.272	−0.053	−0.0477	0.0018	0.0002
2100	0.207	−0.033	−0.0306	0.0035	0.0018

when the additive is present compared to the values obtained under exactly similar conditions in water alone. The changes of the thrust and the torque resulted in a reduction of the propeller efficiency of approximately 5% for 20-ppm average concentration of the polymer. The trends of the thrust and torque and the propeller efficiency show that the reductions due to the presence of the polymer additives are approximately constant when plotted as nondimensional coefficients.

The loss of propeller efficiency of about 5% is well counterbalanced by the presently attainable decrease in overall drag of the body of about 30%. Additionally in the case of normal ship forms the amount of the polymer additive actually passing through the propeller disk, as it washes downstream from the injection points along the hull, will not be expected to be sufficient to produce the 20-ppm concentrations. Thus, the reduction in the propeller efficiency is not expected to reach the measured figure of 5%. This may, however, produce a problem in some applications where the shape of the body and the injection arrangement cause most of the additive to flow through the propeller disk.

Similar tests on a thin nonlifting disk gave the usual torque reduction because of the decrease of viscous resistance and reduction of the drag because of the contraction of the wake behind the disk.

The changed propeller characteristics because of the presence of polymer additives are thought to be because of the increased boundary-layer thickness on the propeller blades and possibly because of the physical attachment of polymer to the leading edges of the blades. This would alter the shape of blade sections affecting the lift and drag characteristics of the sections.

Tests will have to be performed on some basic hydrofoil sections to determine the action of the polymer on the lift and drag of such sections in an effort to explain the reductions in the propeller characteristics.

References

[1] Metzner, A. B. and Astarita, G., "External Flows of Viscoelastic Materials: Fluid Property Restrictions on the Use of Velocity—Sensitive Probes," *A.I.Ch.E. Journal*, Vol. 13, No. 3, May 1967.

[2] Kowalski, T., "Turbulence Suppression and Viscous Drag Reduction by Non-Newtonian Additives," *Transactions of the Royal Institution of Naval Architects*, April 1968.

[3] Little, R. C., "Drag Reduction by Dilute Polymer Solutions in Turbulent Flow," Rept. 6542, May 1967, Naval Research Lab.

[4] Wu, J., "Lift Reduction in Additive Solutions," *Journal of Hydronautics*, Vol. 3, No. 4, Oct. 1969, pp. 198–200.