Lift and Drag Effects Due to Polymer Injections on a Symmetric Hydrofoil

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Experimental results are presented for the effects on the lift and drag of a two-dimensional hydrofoil due to the injection of dilute polymer solutions onto its surface. Results are presented for three different polymers, namely, Polyox, Polyacrylamide, and Jaguar; for the purposes of comparison, results are also presented for water injection. The results indicate that, in general, polymer injection leads to a reduction in drag; but the lift can either increase or decrease depending on the polymer, the angle of attack, the surface on which the injection is made, the chordwise location at which injection is made, and the injection velocity. Results for the effects of the injections on the pressure distributions on the hydrofoil are also presented, and these results are consistent with the force measurements. Examination of the pressure distribution data seems to suggest that the observed lift effects may be due to a boundary-layer displacement phenomenon, with the detailed nature of this displacement effect being dependent on the viscoelastic properties of the injected polymer.

Nomenclature

C_D = drag coefficient, drag force/ $\frac{1}{2}\rho V_f^2$
C_L = lift coefficient, lift force/ $\frac{1}{2}\rho V_f^2$
C_L' = force coefficient normal to the hydrofoil
C_p = pressure coefficient, pressure/ $\frac{1}{2}\rho V_f^2$
c_i = polymer concentrations by weight at the injection slit
c_t = polymer concentrations by weight at the trailing edge
f_p = friction factor for polymer solution
f_w = friction factor for water
l = foil or flat plate length aft of the injection slit
Re^* = Reynolds number; V^*d/ν for pipe, V^*l/ν for foil
s = slit opening width
V_i = velocity of fluid injection
V_f = freestream velocity
V^* = friction velocity; $\sqrt{\tau/\rho}$
α = foil angle of attack
ν = kinematic viscosity of water
ρ = density of water
τ = wall shear stress

I. Introduction

SIGNIFICANT research has been devoted to lift effects associated with drag-reducing polymers since Wq's discovery of pump effects in 1969.[1] Some of the research has involved tests on propellers,[2,3] finite-span hydrofoils,[4] circular cylinders,[5] and two-dimensional hydrofoils[6] in homogeneous polymer solutions. Other research has involved tests on hydrofoils with polymer injection on the foil surface,[7-11] as might be done in the case of a hydrofoil ship.

The present study was a continuation of an earlier research program aimed at the investigation of the lift effects associated with the injection of drag-reducing fluids into the turbulent boundary layer of two-dimensional hydrofoils.[8-10] The earlier research included the lift, drag, and pressure distribution measurements on a 10-cm chord NACA 63_4-020 two-dimensional hydrofoil with and without a polymer (200 ppm of Polyox WSR 301) injection.

One rather surprising result of our early studies[8-10] was that, although polymer injection on the foil surface always led to a drag reduction, under certain conditions this was accompanied by an *increase* in lift. Based on the experimental results, Fruman et al.[10] concluded that the observed lift increases could *not* be explained in terms of changes in the boundary-layer separation point, since the pressure distributions revealed that injection did not significantly alter the pressure distributions in the trailing-edge region. These authors argued that the observed lift effect may not be related directly to the drag-reduction phenomena.

Fruman et al.[10] considered viscoelastic effects as possible explanations for the observed lift changes. They pointed out that when the observed lift forces are plotted against the logarithm of the freestream velocity, a straight-line behavior results in a manner analogous to the behavior noted in pitot-tube measurements in flows containing polymer additives. Such a plot also indicates that there is a threshold velocity below which the lift effect does not appear, the actual value of this threshold velocity being dependent on the test conditions. However, when the results are plotted in terms of the *local* velocity at the injection slit, a single threshold velocity results. These observations lend credence to the concept that a viscoelastic effect may be responsible for the observed lift effects. In particular, they suggest that the injected polymer flow may enter the boundary layer in the form of a "swollen jet" and that this effect may cause the lift changes.

The anamolous lift effect was also noted by Sarpkaya[6] in his tests on two-dimensional hydrofoils in dilute homogeneous solutions of polyethelene oxide, and he concluded that the lift-to-drag ratio of the hydrofoils may either increase or decrease depending on their stall characteristics. Sarpkaya theorized that the observed effect may be due to the different influences of the polymer on the boundary-layer characteristics on the top and bottom surfaces of the hydrofoil and the consequent change in the circulation defect (that is, the difference between the actual circulation and that predicted by the Kutta condition) known to exist[12] in real flows.

The purpose of the present study was to make detailed force and pressure distribution measurements on the existing 10-cm chord hydrofoil with injection of polymers of differing viscoelastic behavior so as to examine whether viscoelastic effects are responsible for the observed lift changes. Moreover, the objective of the present study was also to investigate the effects on lift, drag, and lift/drag ratio of such factors as chordwise location of the injection position, the

Received June 17, 1977; revision received Dec. 2, 1977.
Index category: Hydrodynamics.
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rate of injection, the side (suction or pressure) on which injection is made, and the angle of attack.

II. Experimental Program

Lift, drag, and pressure measurements were performed on the 10-cm chord hydrofoil under the following test conditions:

a) Injected fluids – 1) water, 2) 200 ppm Polyox WSR 301 (Union Carbide), 3) 350 ppm Polyacrylamide (Polyscience – Cat. #2806), and 4) 1500 ppm Jaguar WPB (Stein, Hall & Co., control #23-0548)

b) Injection velocity ratios $V_i/V_f - 0.1$ and 0.3, ($V_f = 11$ m/s)

c) Angles of attack $\alpha - 0$, 2.5 (or 3.25), and 5 deg

d) Injection sides – suction (upper) and pressure (lower)

e) Injection positions – 10% and 30% chord

All tests were performed in the Hydronautics High-Speed Channel (HSC) modified to obtain a two-dimensional flow. The hydrofoil has two 0.00127-cm wide injection slits, one located at 10% chord and the other (on the opposite side) at 30% chord. Each surface of the foil has 10 pressure taps between 18 to 86% chord length. The detailed description of the channel modification, the hydrofoil, and the design of the injection slits is given in Refs. 8 and 10.

Selection of Polymer Concentrations

A series of pipe-flow tests was conducted to obtain the drag reduction-vs-concentration characteristics of each polymer solution at a Reynolds number $Re^* = 3200$, at which the HSC tests were performed. The general description of the test setup and procedure appears in Ref. 13. Tests results are shown in Fig. 1.

For a flat plate, Fruman and Tulin[14] give the following empirical equation that relates the trailing-edge concentration c_t to the injected concentration c_i as follows:

$$c_t = 10.79\left(\frac{V_i}{V_f}\right)^{1.74}\left(\frac{s}{l}\right)^{1.16} c_i^{2.16} \text{ for } l > 7.8\left(\frac{V_i}{V_f}\right)^{1.5} sc_i$$

$$c_t \simeq c_i \text{ for } l < 7.8\left(\frac{V_i}{V_f}\right)^{1.5} sc_i$$

For the HSC tests the polymer concentrations at the injection ports were chosen using the foregoing relation so as to maintain the concentrations of the polymers over the entire hydrofoil in the range corresponding to maximum drag reduction. The values of c_i, i.e., 200, 350, and 1500 ppm for Polyox, Polyacrylamide, and Jaguar, respectively, were selected for the case $V_i/V_f = 0.1$ and $s/l = 0.0014$, corresponding to 10% chord slit; i.e., $c_t = 9$, 30, and 700, respectively. These values of c_i were also used for $V_i/V_f = 0.3$ and 30% chord injection cases. It should be noted that the preceding equation was derived from experimental results for Polyox injection; as such, its use for other polymers may be questionable. Nevertheless, its use was necessary since a rational alternative does not exist.

Measurement Techniques and Repeatability of the Tests

The lift and drag forces were measured by means of four reluctance-type block gages attached to the foil as shown in Fig. 2, whereas the pressures were measured by means of three diaphragm pressure transducers. C_L and C_D curves for the hydrofoil in water without injection are shown in Fig. 3. The slight asymmetry of the hydrofoil due to the presence of the injection slits is responsible for the slight difference in the slopes of the two lift curves. Note that, for the sake of ease of fabrication, only two slits were provided and that the injection slits at the 10 and 30% chordwise stations were located on opposite sides of the hydrofoil. Since data were required for the effects of injection on both sides of the hydrofoil from either chordwise location, the following experimental approach was used: the angle of attack was varied from +5 deg to −5 deg for injections from both chordwise locations, and the results for the negative angles of attack were interpreted in terms of the equivalent case when the angle is positive and when the injection is on the side opposite to the one on which it actually is made. This transposition is legitimate in view of the basic symmetry of the hydrofoil, so long as a consistent sign convention for the direction of the lift is utilized.

Each test of fluid injection was preceded and followed by a no-injection test. As the changes in the force and pressure measurements due to injection are relative to the averages of the immmediately preceding and following no-injection measurements, any polymer buildup (< 1 ppm for Polyox and Polyacrylamide) in the recirculating water has a negligibly small effect on the measurement. As this procedure was repeated for each of the 10 pairs of pressure taps, the lift and

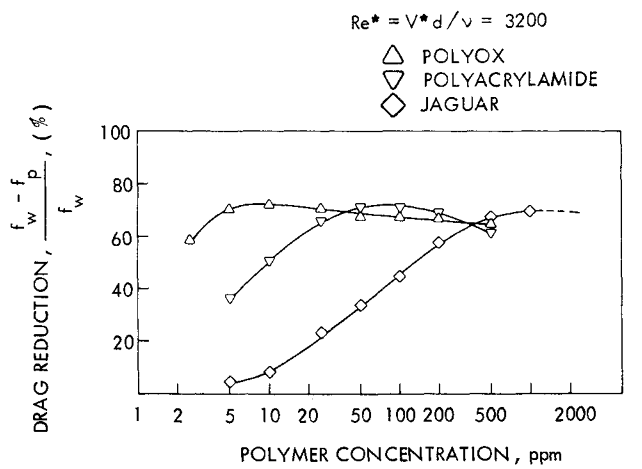


Fig. 1 Effect of polymer concentration on the friction drag in case of a smooth pipe flow.

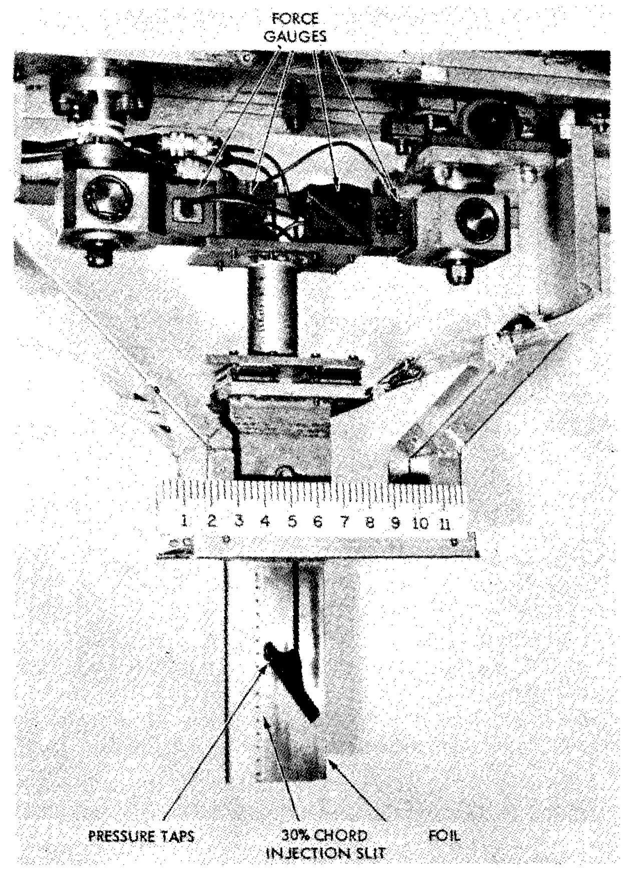


Fig. 2 10-cm chord hydrofoil showing block gage arrangement, injection slit, and pressure taps.

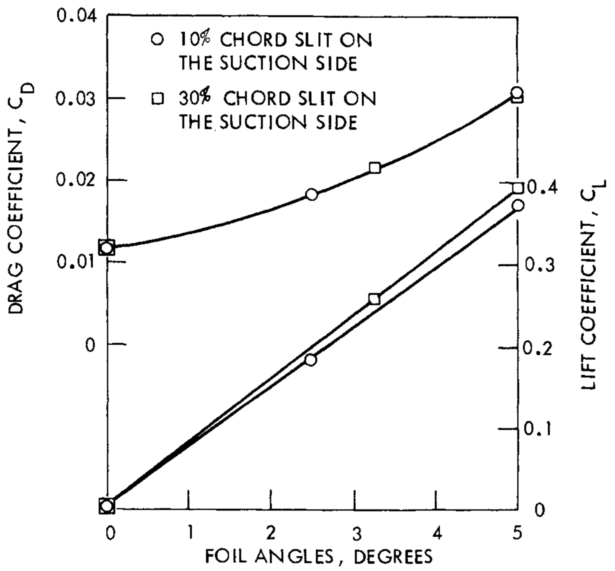


Fig. 3 Lift and drag coefficients for the hydrofoil in water without injection.

drag measurements are the averages of 10 individual measurements with standard deviations less than 1% at $\alpha = 2.5$ and 5 deg. The pressure gages were checked for proper operation by comparing the differences between the pressures measured with two of the gages against the pressure differential of the third gage (Fig. 4). Also shown in Sec. III, the changes in the normal forces, due to polymer injection as measured by the force gages, are in good agreement with those values computed from the relative change in the pressure distribution around the hydrofoil. As only the differences in the measurements due to injections were sought, corrections usually applied to wind-tunnel data and those arising from the lack of true two dimensionality[15] were not applied here. The detailed description on the measurement techniques and repeatability of the tests appear in Refs. 8 and 10. The measurements are sufficiently reliable to define the effects of injections on the net lift, drag, and the pressure distribution.

III. Experimental Results

Drag

Water injection results in a drag increase, or at most, a slight drag reduction; on the other hand, polymer injection always results in a drag reduction (see Figs. 5 and 6).

Lift

As shown in Figs. 7 and 8, water injection always seems to produce a lift force in a direction opposite to the injection side, the magnitude of this lift change being relatively larger for $V_i/V_f = 0.3$ and 10% chord injection cases. Polymer injection produces a lift force in either the same direction as that of the injection or opposite to it, depending upon the polymer (compare Jaguar and Polyox at 0 deg angle of attack and 30% chord injection, Fig. 8), the rate of injection (compare 0.1 and 0.3 rates of injection for Polyox at 0-deg angle of attack, Fig. 7), the location of injection (compare 10 and 30% chord locations for Polyox, pressure-side injection

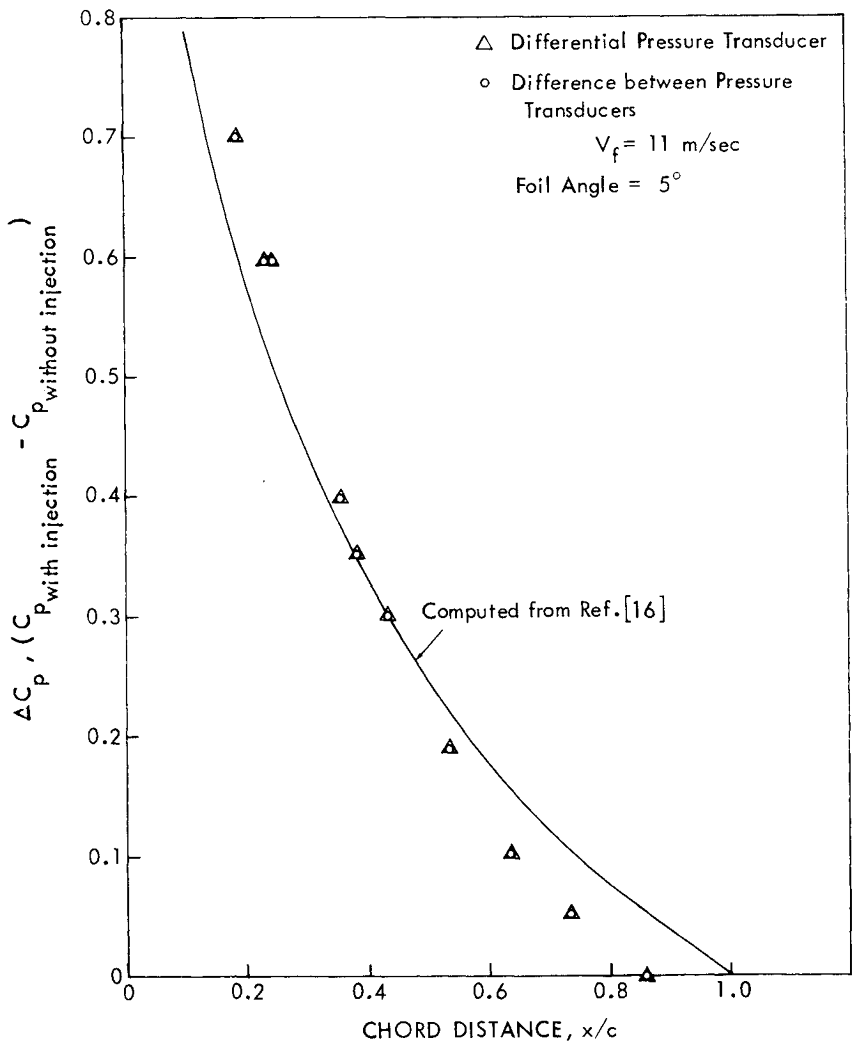


Fig. 4 Comparison between ΔC_p values measured by two different methods during a test with no injection.

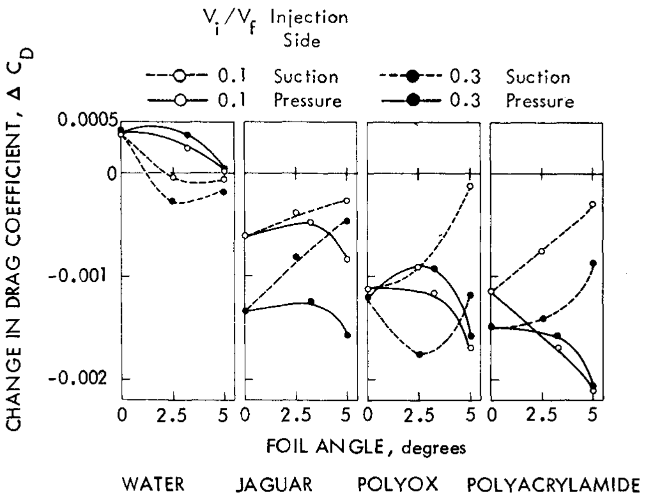


Fig. 5 Effect of 10% chord injection of water and polymers on the drag coefficient of the hydrofoil.

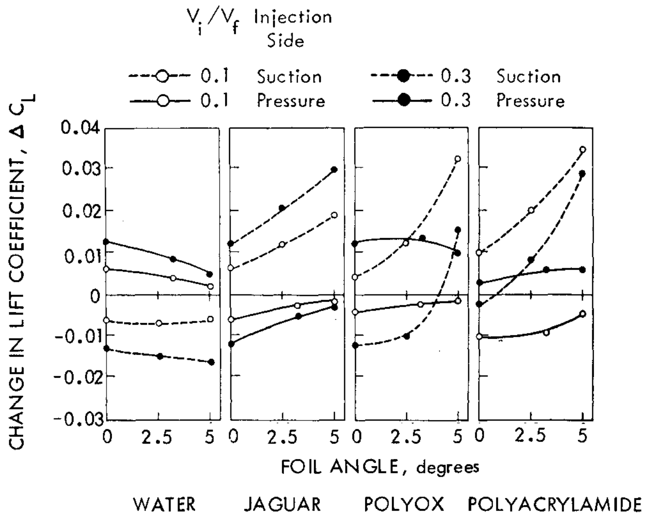


Fig. 7 Effect of 10% chord injection of water and polymers on the lift coefficient of the hydrofoil.

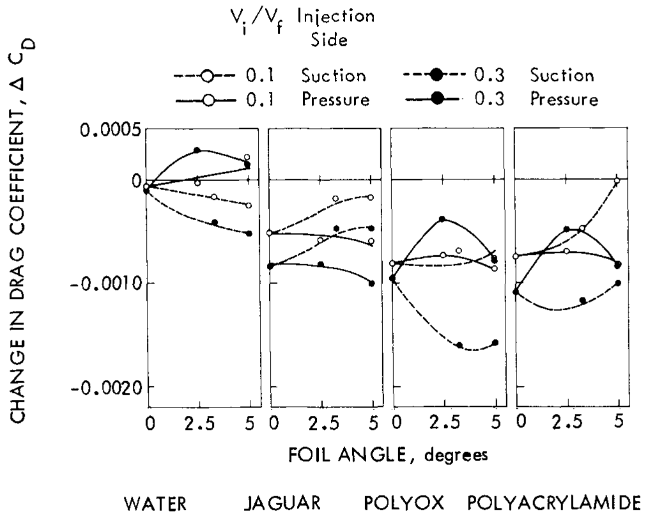


Fig. 6 Effect of 30% chord injection of water and polymers on the drag coefficient of the hydrofoil.

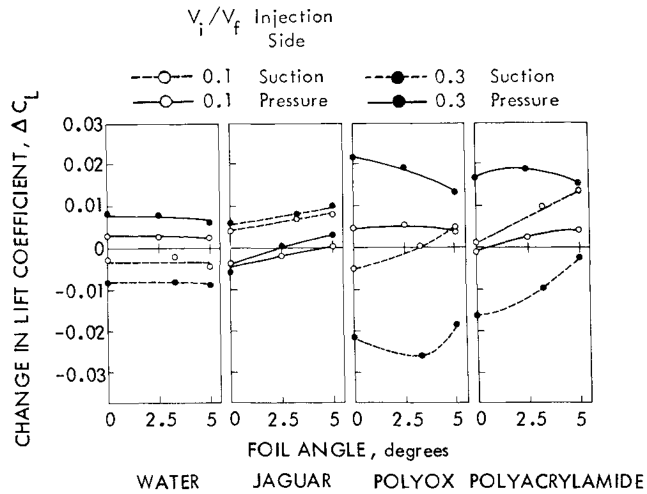


Fig. 8 Effect of 30% chord injection of water and polymers on the lift coefficient of the hydrofoil.

at 0.1 rate, Figs. 7 and 8), and the angle of attack (compare 0-deg and 2.5-deg with 5-deg angle of attack for the suction-side injection of Polyox at $V_i/V_f = 0.3$ rate, Fig. 7).

Lift-to-Drag Ratio

Figures 9 and 10 show that for water injection lift-to-drag ratio increases for pressure-side injection and decreases for suction-side injection. Except for suction-side injection of Polyox and Polyacrylamide at $V_i/V_f = 0.3$ rate, polymer injection increases the lift-to-drag ratio for $\alpha > 2$ deg.

Pressure Distribution

The pressure distribution data were taken for all of the different test conditions. Typical pressure distribution curves are shown in Figs. 11 and 12. The change in the chordwise pressure distribution due to suction-side injections of Polyox and Jaguar at a foil angle of 2.5 deg is plotted in Fig. 11. The hydrofoil has pressure taps only between 18 and 86% of its chord length; nevertheless, the general trend is good enough to make the following observations.

1) Polyox injection at $V_i/V_f = 0.1$ results in a pressure decrease on most of the suction side and in a pressure increase on the pressure side; hence, one would expect a lift increase. On the other hand, Polyox injection at $V_i/V_f = 0.3$ results in a pressure increase on most of the suction side and in a pressure decrease on the pressure side; hence, one would expect a lift decrease. These observations are consistent with the results given in Fig. 7.

2) Jaguar injection at $V_i/V_f = 0.1$ as well as at 0.3 rate results in a pressure decrease on the suction side and in a pressure increase on the pressure side; hence, a lift increase is expected in both cases. However, the magnitudes of this pressure change on both sides are comparatively larger for $V_i/V_f = 0.3$; hence, a relatively larger increase in the lift is expected for that case. Again these observations are very consistent with the results given in Fig. 7.

In Fig. 12a the pressure distribution data for 10% chord suction-side injection of Polyox at foil angle $\alpha = 5$ deg are extrapolated in the no-pressure tap regions close to the leading and trailing edges. Changes in the normal force coefficient obtained by integrating the pressure distributions ($\Delta C'_{L_p}$) are the same, within the demonstrated experimental errors, as those changes obtained from the force measurements ($\Delta C'_{L_m}$). These comparisons demonstrate the self-consistency of the data.

The occurrence of a sharp negative pressure peak in the relative pressure distribution on the side of injection (Figs. 11 and 12a) is a characteristic feature of most of the cases considered. Water injection in some cases gives rise to a positive pressure peak; see Fig. 12b. The magnitude and the chordwise extent of this peak have an important bearing on the net lift change due to injection.

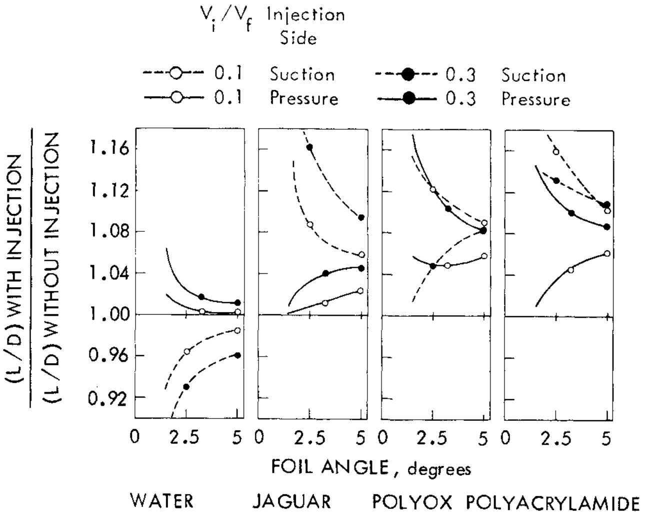


Fig. 9 Effect of 10% chord injection of water and polymers on the lift-to-drag ratio of the hydrofoil.

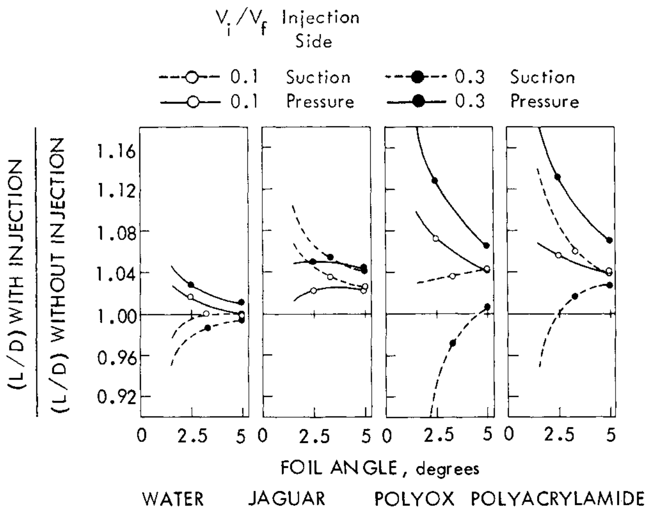


Fig. 10 Effect of 30% chord injection of water and polymers on the lift-to-drag ratio of the hydrofoil.

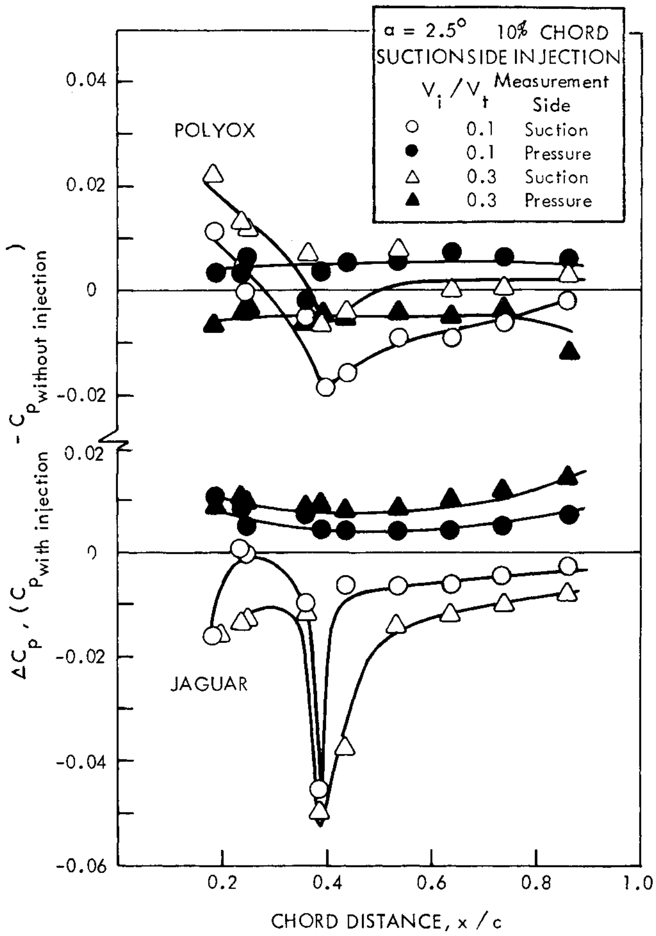


Fig. 11 Difference in pressure coefficient ΔC_p vs chord distance x/c.

IV. Discussion of the Results

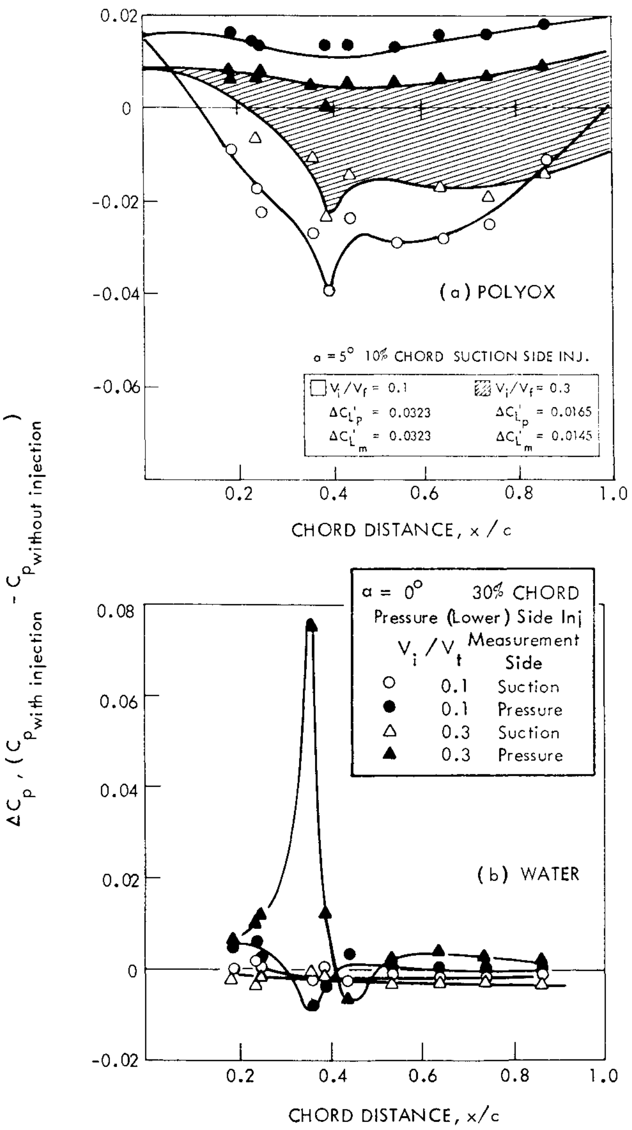
As can be seen from Figs. 5-8, different polymers lead to significantly different results. In particular, as already noted, the lift behavior due to injection seems to be significantly different for the different polymers and for water. Examination of the detailed pressure distribution data gives some insight as to how the polymer injection under different test conditions affects the net lift forces. The comparisons between the pressure distribution data and the lift forces given in the preceding section not only provide evidence of excellent self-consistency of the data but also show that there are some fundamental differences in the pressure distributions for different polymers (compare the pressure distribution data for Polyox and Jaguar injection at $V_i/V_f = 0.3$ rate, Fig. 11).

One important feature of the relative pressure distributions that is worthy of special attention is the sharp decrease in the pressure coefficient some distance aft of the injection position. This sharp negative peak in the pressure distribution is a characteristic feature of most of the cases considered, *and always occurs on the same side on which the injection is made.* The magnitude and chordwise extent of this peak have an important bearing on the magnitude as well as the direction of the net lift change that results due to the polymer injection.

As mentioned earlier, Fruman et al.[10] have suggested that the lift effect of polymer injection may be due to the fact that polymer stream enters the flow around the hydrofoil in the form of a "swollen jet" due to the viscoelastic behavior of the polymer solution. While it is plausible to suppose that the observed peaks in the pressure distribution may be due to these "swollen jets," it is paradoxical that *water* injection also leads to peaks in the pressure distribution, as illustrated in Fig. 12b. This figure shows the changes in the pressure distributions resulting from water injection at an angle of attack of 0 deg for lower-side injection at 30% chord. For the corresponding case of Polyox injection, there is a negative peak on the bottom-side pressure distribution (the side on which the injection is made). However, for the case of water injection, although there is a small negative peak for the smaller rate of injection, the pressure peak becomes *positive* for the larger rate of injection. Thus, it is difficult to attribute the observed pressure peaks to a "swollen jet" effect.

In many cases, as in the case of Polyox injection illustrated in Fig. 11, there are positive pressure regions preceding and following the negative pressure peaks. Also, the pressure distribution is affected everywhere on the foil surface regardless of the side or location at which injection is made. Moreover, the actual location at which injection is made seems to have little or no influence on the location of the pressure peak, the latter apparently being influenced more by the basic undisturbed pressure distribution on the hydrofoil.

As already mentioned, based on his experiments on hydrofoils *immersed* in dilute, homogeneous polymer solutions, Sarpkaya[6] has suggested that the observed lift increases may be due to the restoration, by polymer-induced changes, of some of the circulation reduction created by boundary-layer displacement effects. The present results on the effects of the polymer when it is *injected* at the hydrofoil surface also seem to suggest that the observed lift changes may be due to a boundary-layer displacement effect caused by



the injection, especially in view of the differences between the actual measured pressure distributions under undisturbed conditions (that is, in the absence of injection) and theoretical computations based on thin-airfoil theory[16] (see Fig. 4). The significant differences between the calculated and measured pressure distributions, especially near the trailing edge of the hydrofoil are well known in the literature,[12,17-19], and are attributed to boundary-layer effects. The potential-flow streamlines around the hydrofoil are displaced outward not only because of the thickness distribution of the hydrofoil but also because of the boundary layer on the foil surface. Hence, better results would be obtained if, in the computations, instead of using the actual hydrofoil shape, an altered shape in which the boundary-layer-displacement thickness is added to the shape is used.

The relevance of these remarks in the present context is that, as can be seen from Fig. 4, the boundary-layer-displacement effects can have a significant effect on the pressure distributions, these effects being considerably larger than the observed lift effects caused by polymer injections. Thus even small changes in the dynamic evolution of the boundary layer on the surface on which the injection is made can be expected to produce changes in the pressure distributions of the kind observed in the present experiments. The present test results, like those reported earlier by Sarpkaya,[6] suggest that the lift effect may be attributed to the changes caused by the polymer on the boundary-layer-displacement effects. However, the observed effect evidently is also a function of the characteristic relaxation time τ of the polymer or, more appropriately, the nondimensional parameter $V\tau/l$, where V is the freestream velocity and l is a characteristic hydrofoil dimension. The data also show that the boundary-layer-displacement effect must also be a function of the side, location, and velocity of the polymer injection.

V. Concluding Remarks

Tests were conducted on a 10-cm chord, NACA 63_4-020 two-dimensional hydrofoil to investigate the effects of injection of water and three different polymers, namely, Polyox, Polyacrylamide, and Jaguar, at various locations on the foil surface. The results show that water injection causes a drag increase, or at most, a slight drag reduction; whereas polymer injection always yields a drag reduction. Moreover, water injection always seems to produce a lift force in a direction opposite to the side of injection, whereas polymer injection produces the lift force in either the same direction as that of the injection or opposite to it, depending upon the polymer, the angle of attack, as well as the rate, side, and location of the injection.

Comparisons between the measured lift values and the pressure distributions data offer evidence of the excellent self-consistency of the results. The relative pressure distribution in general is affected everywhere on both foil surfaces, regardless of the side and location of the injection; and in particular, displays a sharp pressure peak on the side of the injection some distance aft of the injection slit. The exact location of this pressure peak seems to be related more to the nature of the basic undisturbed pressure distribution on the foil surface and less to the actual chordwise location of the injection.

The results presented herein complement the data given earlier by Sarpkaya[6] on effects on lift and drag of hydrofoils immersed in *homogeneous* polymer solutions. The present data also seem to support Sarpkaya's suggestion that the observed lift behavior may be caused by the influence of the polymer on the circulation reduction created by boundary-layer-displacement effects. This hypothesis can be varified directly, since the measured pressure distributions can be analyzed using classical thin-airfoil theory, and the "effective hydrofoil shape" that will produce the observed pressure distributions can be calculated. This effective hydrofoil shape then can be viewed in terms of a change in the evolution of the boundary layer around the actual hydrofoil. By these means, correlations can be sought between the observed effects and the test variables in terms of information that exists in the literature on the behavior of boundary layers under favorable and adverse pressure gradients, and under the influence of injections and various surface perturbations. Such calculations are presently being carried out utilizing the large body of data acquired under the present study, and the results will form the basis for a future paper.

Acknowledgments

The results contained in the present paper are the outcome of a research program supported by the Fluid Dynamics Branch, Office of Naval Research, under Contract No. N00014-77-C-0070. Technical monitoring for the program was provided by Stan Doroff and Ralph Cooper of ONR.

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