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DRAG REDUCTION BY EJECTING ADDITIVE SOLUTIONS INTO A PURE-WATER BOUNDARY LAYER

By

Jin Wu and Marshall P. Tulin

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ABSTRACT

Drag reduction caused by ejecting additive solutions from a slot into a pure-water boundary layer on a flat plate has been systematically studied. Results include drag measurements for a plane boundary, smooth and rough, with various openings of the slot and with various concentrations and discharges of the ejected additive solution. Conclusions have been drawn on the additive requirement in external flows and on the ejection technique for an optimum drag reduction.

LIST OF FIGURES

INTRODUCTION

Many experiments show the capability of additives of high molecular weight to reduce turbulent friction. Most measurements refer to the pressure drop in turbulent pipe flows with additives homogeneously mixed in water. These are the internal flow cases, where the homogeneous additive solution flows constrained in a fully developed boundary layer. However, this does not resemble the case for external flows, where the additive solution has to be ejected into a developing boundary layer of pure water. There exists uncertainty about techniques for the most efficient ejection into external flows. It may not be required in external flow cases that the entire boundary layer should be filled with polymer solution, because the major effects due to the presence of additive solutions occur very close to the wall and certainly within the inner boundary layer (Reference 1). For very dilute solutions this is especially true, as shear-stiffening occurs in the turbulent region closest to the wall and, it is believed, accounts for the reduction of turbulent skin friction due to its action there. It is not advised that a highly concentrated additive solution be ejected at the wall and then to let turbulent mixing inside the boundary-layer dilute the ejected solution. Since turbulent mixing between the ejected solution and the pure-water surrounding may be highly suppressed (Reference 2), the ejected solution may remain too concentrated and may therefore lose its effectiveness.

In a previous study (Reference 3), the turbulent friction of a plane boundary in flows of homogeneous solutions of high-molecular-weight additives was measured and compared with that produced by ejecting additive solutions into the pure water boundary layer of a flat plate (Reference 4). The results indicate that the ejected solution is mixed but very poorly with its pure water surroundings. Visual studies concerning diffusion and entrainment of jets with additive solutions flowing into a turbulent stream of pure water confirm that additives suppress turbulent diffusion. Based on these results, it was suggested (Reference 4) that for drag reduction in external flows the solution ejected into the boundary layer should be dilute, that the rate of ejection should be comparable to the discharge within the inner boundary layer (the wall controlled region), and that the normal component of the ejection velocity as well as the difference between the ejection velocity and the stream velocity should be minimized.

In the present study, the friction of a plane boundary, smooth and rough, has been systematically measured with additive solutions (Polyex WSR-301) of various concentrations and discharges, ejected from a slot of adjustable width. The results not only confirm the previous suggestions but further indicate in a quantitative fashion optimum techniques of additive ejection rate. It is shown that under the circumstances of the present tests, a very small amount of additive is actually needed for

the most effective application to achieve drag reduction in external flows: concentrations of between 100 and 1000 ppmw at the viscous-sublayer discharge for a smooth surface, and at the mixing-layer discharge for a rough surface. It remains to be seen whether these conditions are also optimum in the case of larger plates and higher Reynolds numbers than were so far considered.

EXPERIMENTAL TECHNIQUE

Measurements of Turbulent Friction

The experiments have been performed in a circulating water channel with a closed test section 44 in. long, 15 in. wide, and 7.5 in. deep. A part of the cover plate at the test section, 10 inches wide and 21 inches long, is cut from the rest with a clearance of 1/100 in. along four sides; see Figure 1. This part of the cover plate is held by a strain-gage support whose output is indicated on a digital readout device. A strip of No. 32 sand blast, 1 inch in width, was placed 3/8 in. upstream from the leading edge of the ejector. Therefore, the sand serves for turbulence stimulation, but its resistance is excluded in the drag measurements.

The drag-measuring plate was also roughened by gluing to its surface spherical particles having a diameter of 0.108 in. and arranged in a random and in the most compact form, or hard-rubber mats with pyramidal roughness, having a height of 0.062 in. and at a spacing of 0.169 in.

Ejection of Additive Solutions

The test fluid consists of aqueous solutions of variously concentrated polyethylene oxide (Polyex WSR-301) additive. The additive solution is ejected from a slot-ejector, shown in Figure 1. The ejector is installed transversely upstream from the plane boundary, having the slot at 1-3/16 in. from the leading edge of the plane boundary. Near tangential ejection is achieved as the plane containing the slot is at an inclination of 7° from the plane boundary. The width of the slot opening is adjustable; this adjustment and the use of additive solutions of various concentrations and of various discharges enable us to obtain different initial velocity and concentration distributions of the ejected additive solution.

RESULTS

A series of measurements of the turbulent friction on the plane boundary, smooth and rough, using homogeneous solutions of polyox additives were conducted earlier. The results, portions from Reference 4, are shown in Figure 2. The drag reduction obtained from the rough surface with glass beads is seen to be similar to that from the smooth surface. A continuous curve, drawn through the data points, will be used to compare with the drag reduction obtained in ejection studies.

The ejection studies were conducted at a constant channel velocity of 8 ft/sec. The Reynolds number defined with the length of the plane boundary is 1.3×10^6. For each slot opening of these studies, a series of experiments, ejecting additive solutions of various concentrations, were systematically conducted. Different discharges of additive solutions were ejected for each additive concentration to cover the most interesting range, showing a rapid variation of drag reduction with discharge. During the experiment, the turbulent friction of the plane boundary was measured on two occasions, one before and the other during ejection. The drag reduction obtained by taking the difference of two readings was further corrected to eliminate the reduction due to ejection itself and to retain only the influence of additive solutions. This correction was based on a pre-test calibration obtained by ejecting pure water at various discharges under the same experimental condition. Because the ejection discharge is very little in comparison with the boundary-layer discharge, this correction is generally small, and does not exceed about 5 percent of the total turbulent friction of the smooth surface and is negligible for the rough surface.

A set of sample results for the smooth surface for one slot opening, is shown in the upper half of Figure 3. For each concentration, the drag reduction was plotted versus the discharge of additive solution. A continuous curve was then fitted to smooth the data and to relate the drag reduction with the

ejection discharge. From the faired data, the drag reduction obtained with different additive concentrations at any given ejection discharge can be determined; see the lower half of Figure 3, where Q_s, as shown later, is the viscous sublayer discharge. This procedure is necessary because it is impractical to introduce the additive solutions of various concentration at any desired discharge.

Following the same procedure outlined in the foregoing paragraph, drag-reduction results with other slot openings and from different surfaces can be obtained; see Figures 4, 5, 6 and 7. It is noted in the last figure that additive solutions of higher concentrations were ejected. The results over a smooth surface with various openings of the ejector and with the ejection discharge at various multiples of the viscous sublayer discharge are compared in Figure 8. The results from smooth and from rough surfaces are compared in Figure 10.

DISCUSSION

Additive Requirements and Ejection Techniques for Smooth Boundary

The nominal thickness of a viscous sublayer, δ, is generally considered to be (Reference 5)

$$\frac{\delta u_*}{\nu} = a = 11.6 \qquad [1]$$

where u_* is the shear velocity, τ_o/ρ (τ_o is the wall stress and ρ is the density of the fluid); and ν is the kinematic viscosity of the fluid. A virtually linear velocity gradient, $\tau_o/\rho\nu$, persists within the sublayer, of which the discharge per unit width, Q_s, can be found as

$$Q_s = \frac{1}{2} \cdot \delta \left(\delta \cdot \frac{\tau_o}{\rho \nu} \right) = \frac{a^2}{2} \nu = 67.3 \nu \qquad [2]$$

It is seen that the normal viscous sublayer discharge is independent not only of the boundary shear but also, more interesting, of the distance from the leading edge of the solid boundary. This implies that the viscous sublayer is enclosed by a streamline, or the viscous sublayer flows inside a stream tube. Consequently, the mass transfer between the viscous sublayer and its surroundings involves diffusive rather than convective processes.

The discharge of the viscous sublayer is seen in Equation [2] to vary with the square of the dimensionless viscous-sublayer thickness and with the kinematic viscosity of the fluid. With additive solution, drag reduction is generally accompanied by an increase of this dimensionless thickness (Reference 6). In addition, the viscosity of dilute additive solutions increase with the additive concentration. Consequently, the discharge of the viscous sublayer with ejection of additive solutions is

certainly greater than that indicated by Equation [2]. However, our method here is to correlate the ejection discharge with the sublayer discharge for a pure water boundary layer.

This study was planned specifically to investigate requirements and techniques for ejecting additive solutions into a pure-water boundary layer for the most efficient drag reduction. Relevant questions and answers are:

(1) For an ideal ejection, what is the most economic way of using additive for drag reduction in external flows?

The drag reduction with various slot openings, concentrations, and ejection discharges shown in the lower halves of Figures 3, 4 and 5 clearly demonstrate the following trends:

(a) For a given slot and with additive solutions of a given concentration, the drag reduction generally increases with the discharge when the ejection rate is small or comparable with the sublayer discharge; the rate of increase slows down when the ejection rate is greater than twice the sublayer discharge; the drag reduction no longer increases, or even decreases when the ejection rate is greater than about five times the sublayer discharge.

(b) The drag reduction at various concentrations with the additive solution ejected at 1, 2, and 4 times the viscous sublayer discharges are shown in the lower halves of Figures 3, 4 and 5. It is seen that a significant drag reduction is provided by ejection at the viscous-sublayer discharge. The gain of drag reduction with higher ejection rate is not overwhelming.

These trends indicate that the ejection rate at the viscous sublayer discharge is probably close to the most effective (economic) way to use additive for drag reduction in external flows. This is substantiated by the results showing that relatively little gain is obtained when the ejection discharge is increased by two or four times the viscous sublayer discharge. Sometimes even less drag reduction was obtained at higher ejection rates, especially with high additive concentrations, probably because the ejected solutions failed to mix with the surrounding pure water and resulted in less drag reduction, see also Figure 2.

(2) What slot configuration should be adopted?

The slot configuration is defined by two parameters, namely, the angle of inclination and the opening of the slot. It is obvious that the

angle of inclination of the slot should be small so that the ejected additive solution will be kept near the wall. The effect of ejection angle on drag reduction was not investigated here. The ejection angle was limited by the convenience of constructing the ejector.

The width of the slot opening should be comparable with the thickness of the sublayer. However, the velocity of the ejection sheet is also related to the slot opening. The comparison of this velocity with boundary-layer velocities governs the mixing between the ejected additive solution and the surrounding pure water. The results obtained from a given ejection angle but with different slot openings are compared in Figure 8. The velocity of the ejection sheet in the present experiment is generally less than the average viscous-sublayer velocity. Consequently the narrowest slot provides the best matching of the ejection velocity with the boundary-layer flow. In addition, the thickness of the viscous sublayer is about 0.005 in. The slot opening should not be too much greater than this thickness (within an order of magnitude) in order to avoid the diffusion of additive solution away from the wall. The results shown in Figure 8 are very much in line with our discussions presented here.

(3) What should the concentration be of the ejected additive solution?

Typical results obtained from the present (ejection) study are compared in Figure 9 with earlier results with uniform solutions over the same plane boundary. These curves are different in shape: the drag reduction curve with uniform additive solutions is seen to be rather peaked, while the curve with ejection features a plateau. The former indicates that highly concentrated additive solutions are relatively ineffective for drag reduction. The latter reveals that the ejected additive solution is diluted by the boundary-layer flow. It is expected that with further increase of ejected additive concentration, or of ejection discharge, the boundary layer flow near the wall will fail to dilute sufficiently the additive solution, and a drop of drag reduction will result.

The dilution of the ejected additive solution is indicated by the shift toward higher concentrations of the ejection curve relative to the curve with uniform solution. The dilution in the present case is deduced to be about one to ten. As the length of the boundary increases, increasing dilution along the length of the plate should

cause the drag reduction curve to shift further toward the high concentration end. More studies are needed in order to investigate in detail the dilution process which is of much importance for the practical application of additives for drag reduction.

(4) In which portion of the boundary layer do additives act to cause drag reduction?

This question can only be answered adequately by a detailed survey of additive concentration within the boundary layer and a systematic comparison of the measured profiles with the drag reduction results. However, it is clear from Figures 3, 4 and 5 that an increase in ejection discharge failed to cause significant increase in drag reduction. This indicates that additive solution need only to fill the viscous sublayer and the innermost region of the turbulent boundary layer in order effectively to cause drag reduction.

Additive Requirement and Ejection Techniques for Rough Boundaries

A detailed boundary-layer measurement over the same rough surface with glass beads was conducted by Wu (Reference 7). It was shown that a constant velocity persists in a region within a quarter of the particle size from the top of the bead. A very strong turbulent mixing undoubtedly exists in this region, which

presumably erases the usual strong velocity gradient near the wall. Therefore, the roughness not only disrupts the viscous sublayer but also introduces a very strong mixing layer near the wall. The discharge of the mixing layer is about ten times that of the viscous sublayer (Reference 7). The additive solution ejected at the wall is then diffused very rapidly in this mixing layer. Consequently, more additive is required; higher ejection rates or additive solutions of higher concentrations should be ejected to be strongly diluted by the mixing due to roughness. No detailed boundary layer survey was performed over the rough surface on the rubber mats. The roughness elements in this case were somewhat smaller in height, but the elements somewhat more widely spaced. Moderate spacing is known (Reference 8) to make the surface relatively rougher in comparison with the same roughness elements placed in the most compact arrangement. In other words, the flow condition over these two rough surfaces may not be appreciably different.

The results obtained with the rough boundaries are shown in Figures 6 and 7. Compared to the data over the smooth boundary, these results show a large effect of ejection discharge over the range tested. The results obtained from the rough surface are compared with those from the smooth surface in Figure 10. It is interesting to see that the data from the rough surface is generally shifted with respect to the data from the smooth surface, toward the high concentration end. The ratio, seen in Figure 10,

of the additive concentrations required for the most efficient drag reduction seems to be about one to five or ten, the same order as the ratio between the viscous-sublayer discharge and that of the roughness mixing layer.

CONCLUSIONS

A systematic drag reduction study was conducted by ejecting Polyox (WSR 301) additive solutions into a pure water boundary layer over both smooth and rough surfaces. The results were compared with an earlier study involving uniform additive solutions. It is recommended that for the most effective drag reduction with additive in external flows, the slot ejection angle should be small with respect to the flow direction and the slot opening should be comparable with the thickness of the viscous sublayer. It was shown that a large drag reduction was obtained by ejecting the additive solution at a rate comparable to the normal viscous-sublayer discharge. This range of discharges is recommended to be the most economic. The choice of additive concentration of the ejected solution is governed by the length of the boundary and its roughness. In the present case (short plate), optimum additive concentrations were found to be $10^2 - 10^3$ ppm for the smooth plate and an order of magnitude larger for rough surfaces where a wall mixing due to roughness causes increased dilution of the ejection solution.

ACKNOWLEDGMENT

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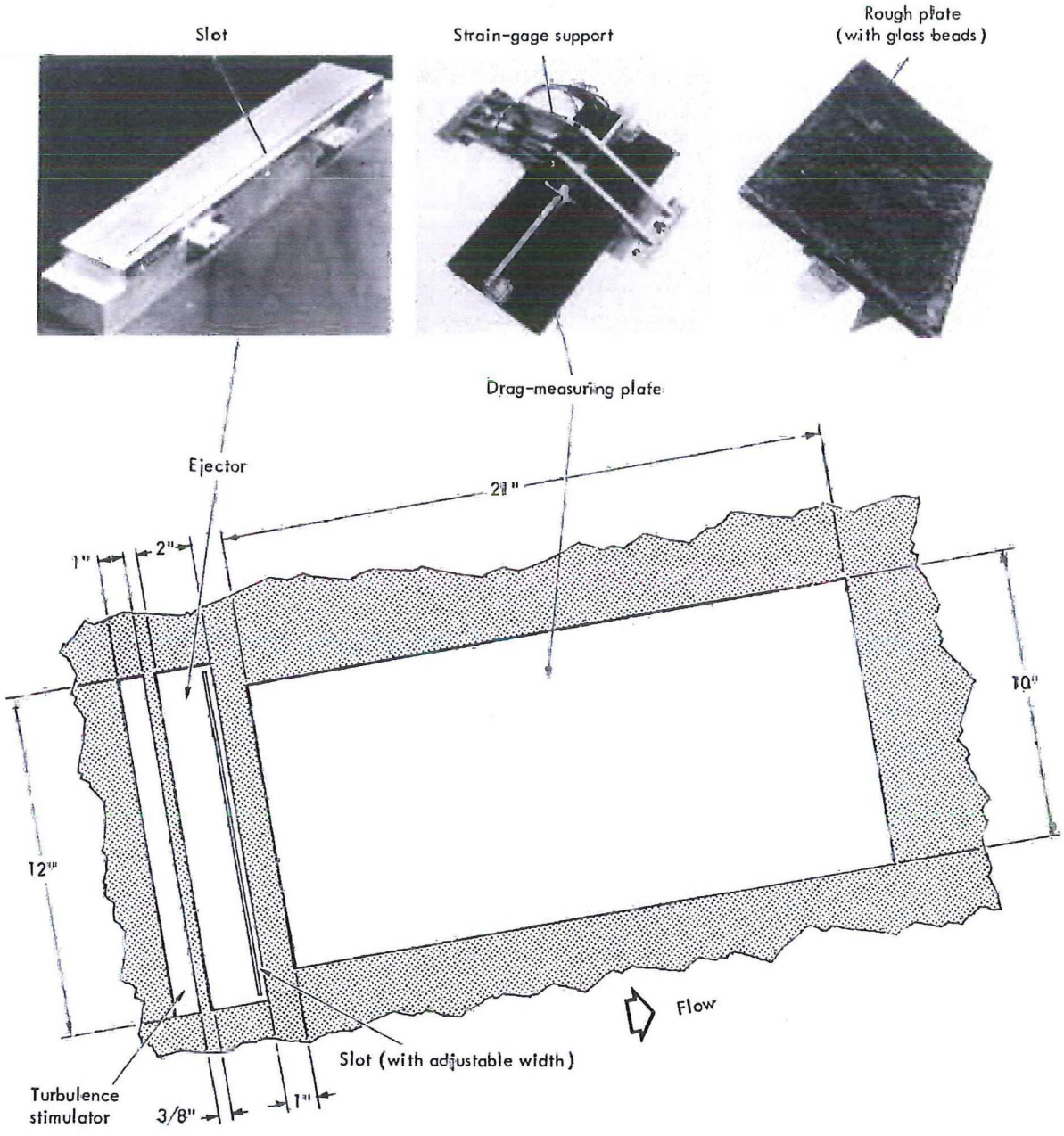


FIGURE 1 - GENERAL VIEW OF EQUIPMENT

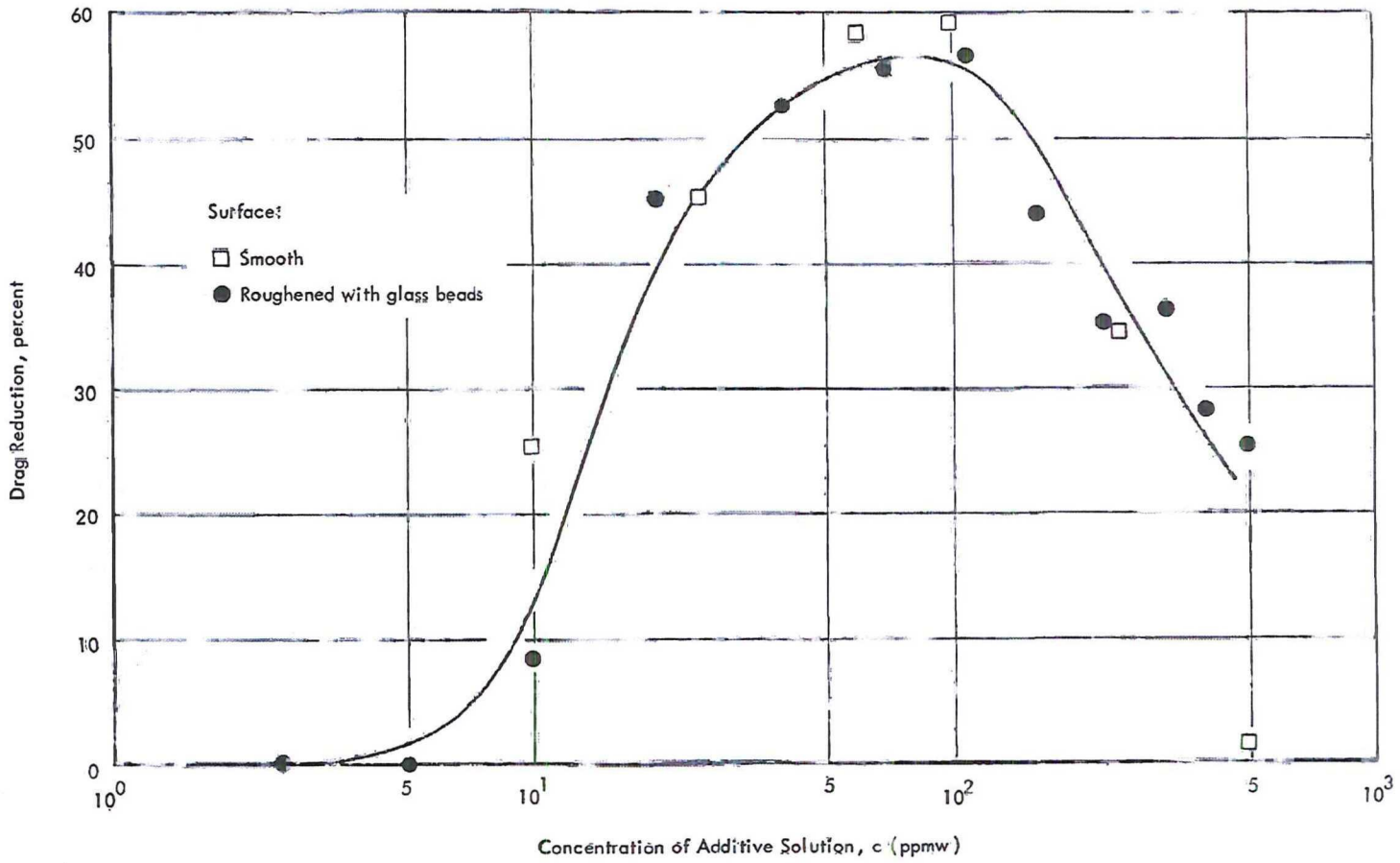
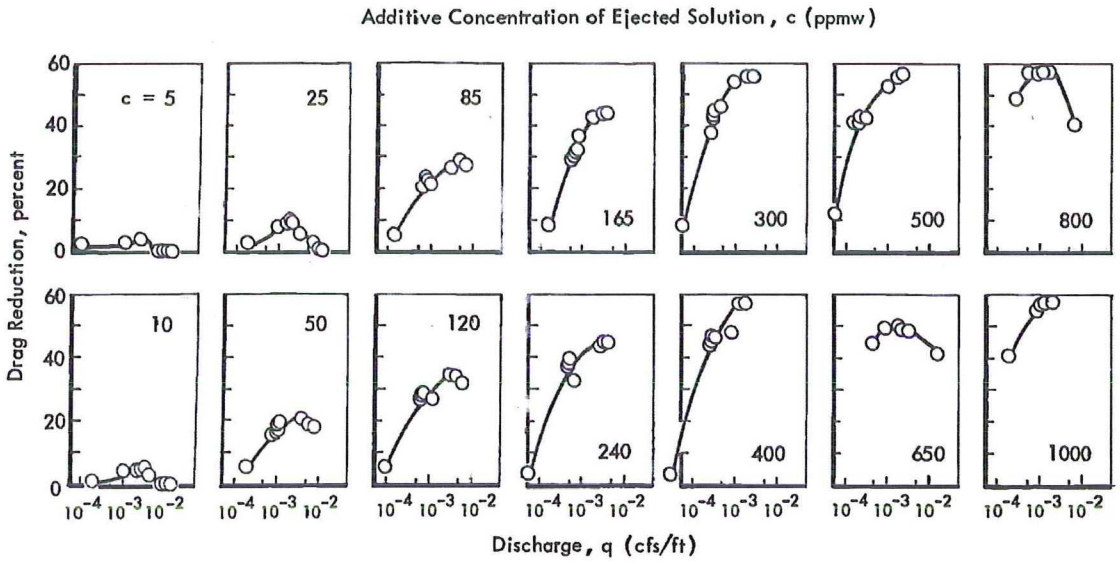


FIGURE 2 - DRAG REDUCTION OF SMOOTH AND ROUGH BOUNDARIES WITH HOMOGENEOUS ADDITIVE SOLUTIONS.



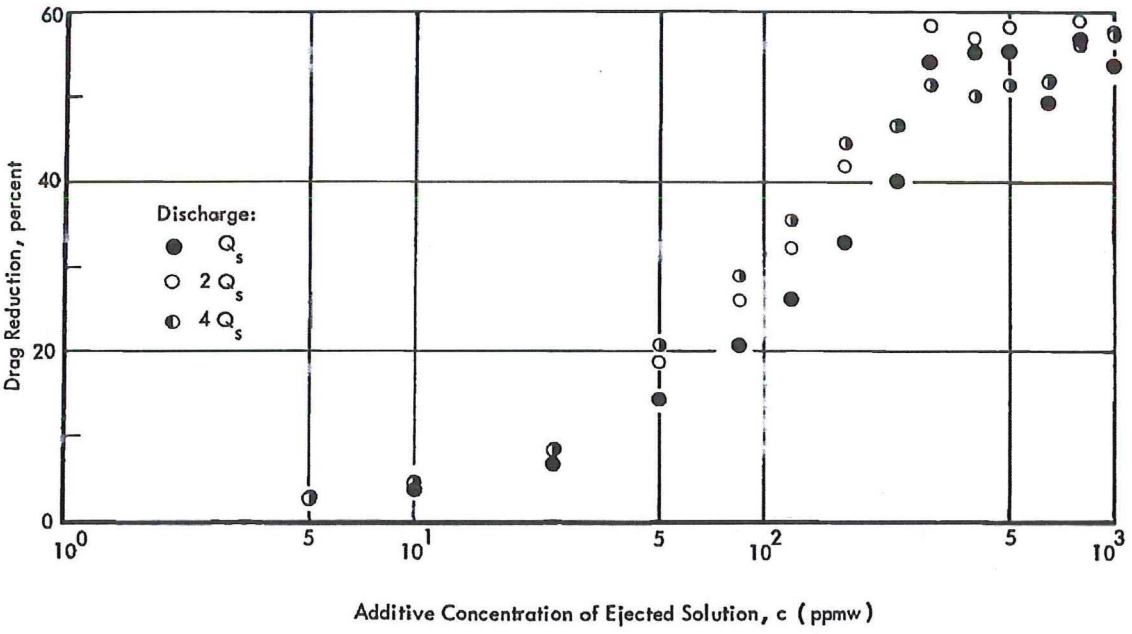
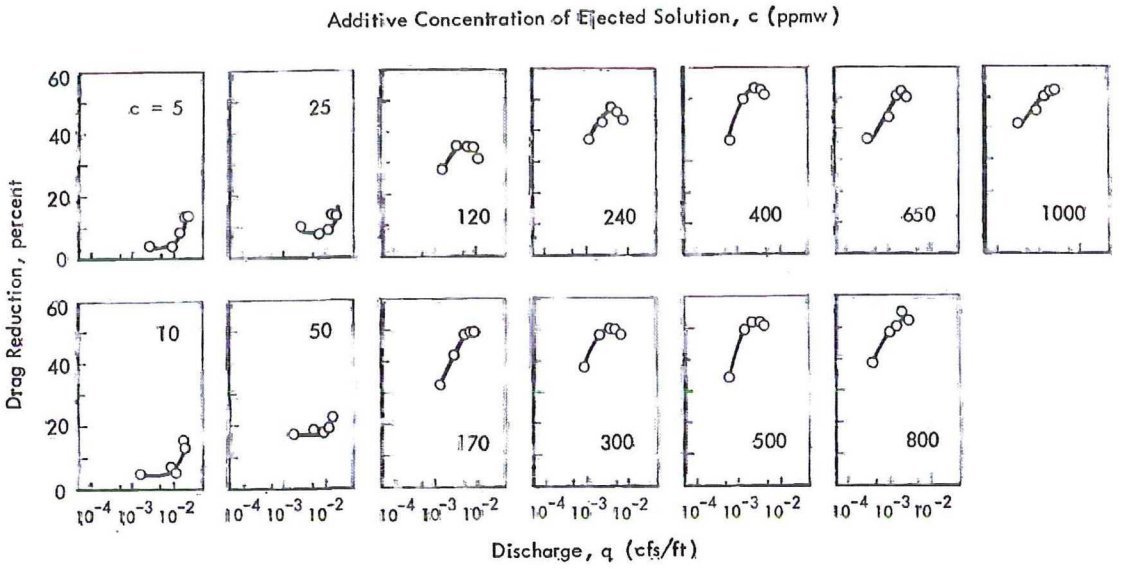


FIGURE 3 - DRAG REDUCTION BY EJECTING ADDITIVE SOLUTIONS INTO A PURE-WATER BOUNDARY LAYER OF A SMOOTH SURFACE (SLOT OPENING 0.022 INCHES)



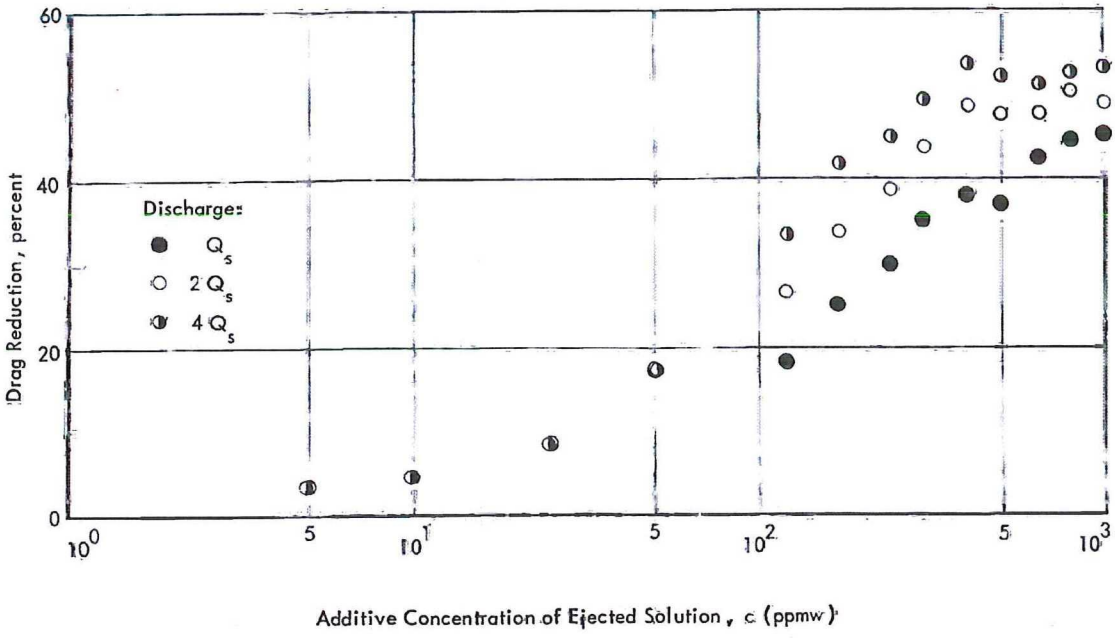
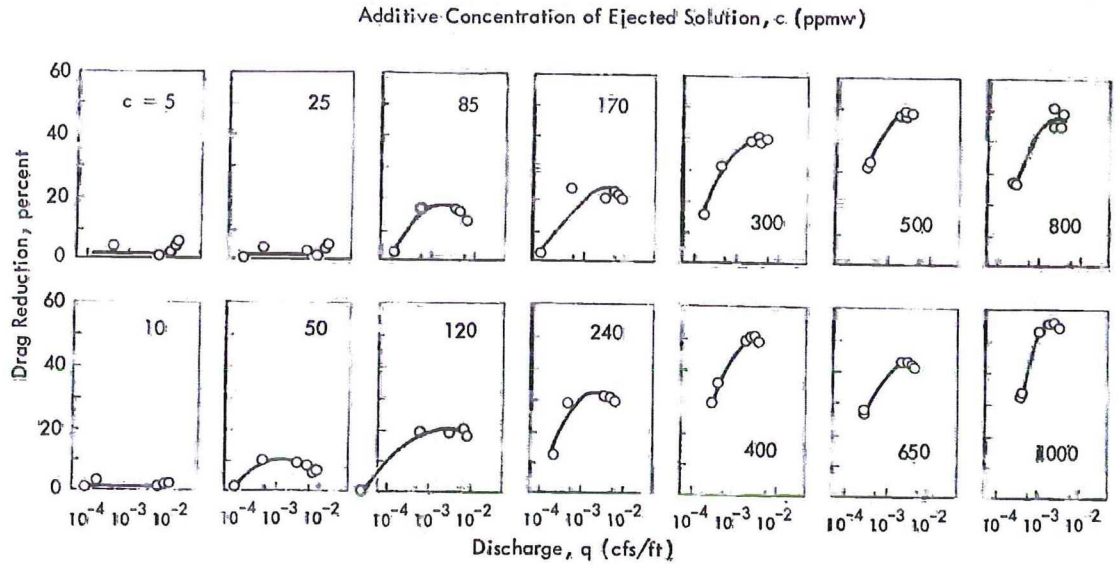


FIGURE 4 – DRAG REDUCTION BY EJECTING ADDITIVE SOLUTIONS INTO A PURE-WATER BOUNDARY LAYER OF A SMOOTH SURFACE (SLOT OPENING 0.042 INCHES)



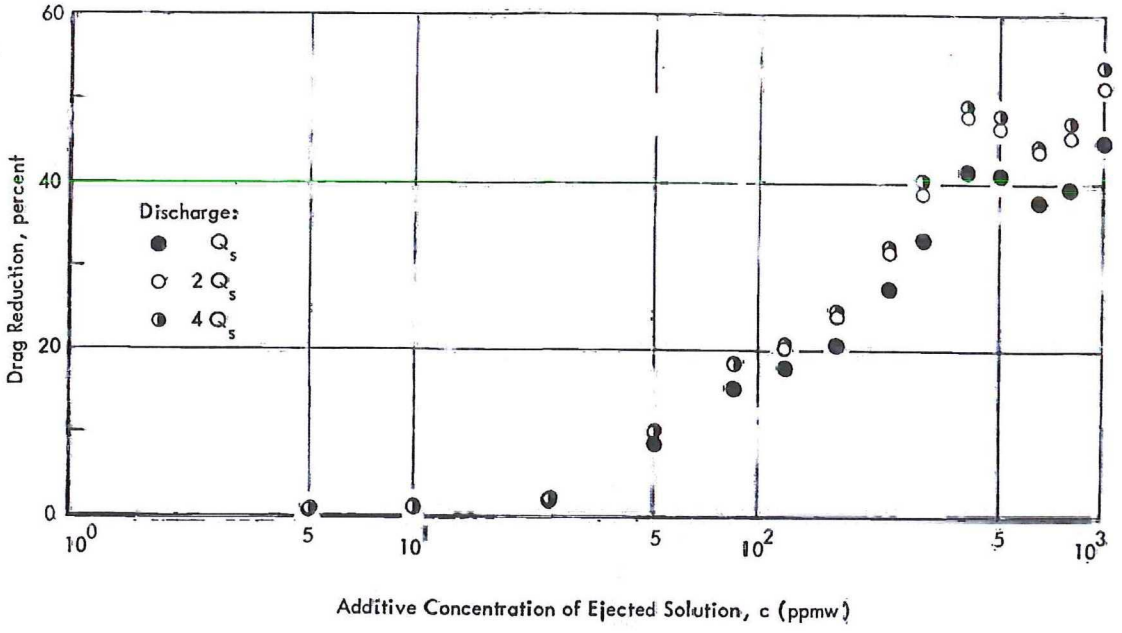
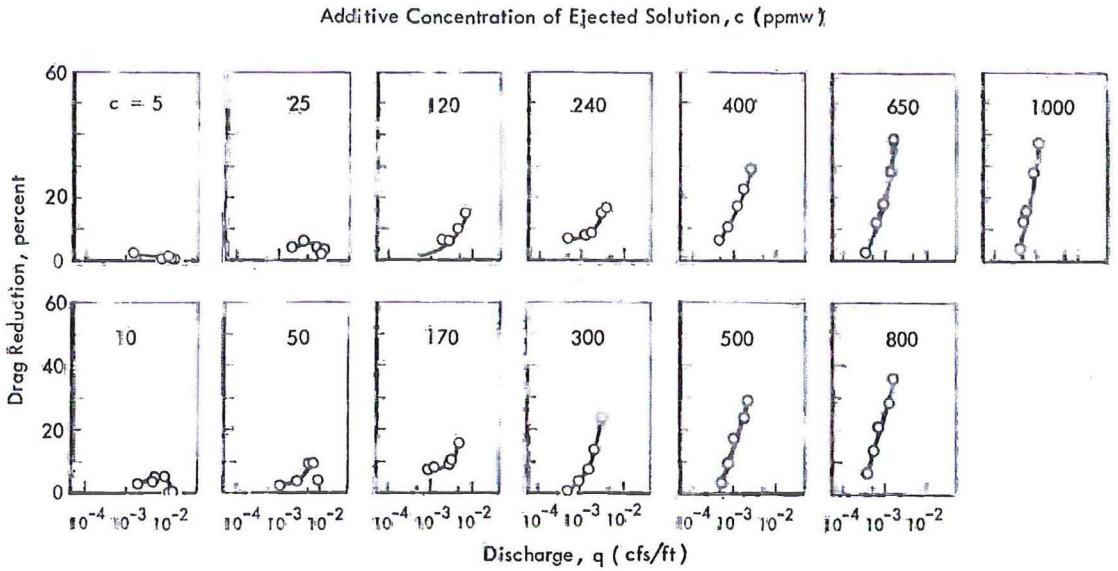


FIGURE 5 – DRAG REDUCTION BY EJECTING ADDITIVE SOLUTIONS INTO A PURE-WATER BOUNDARY LAYER OF A SMOOTH SURFACE (SLOT OPENING 0.093 INCHES)



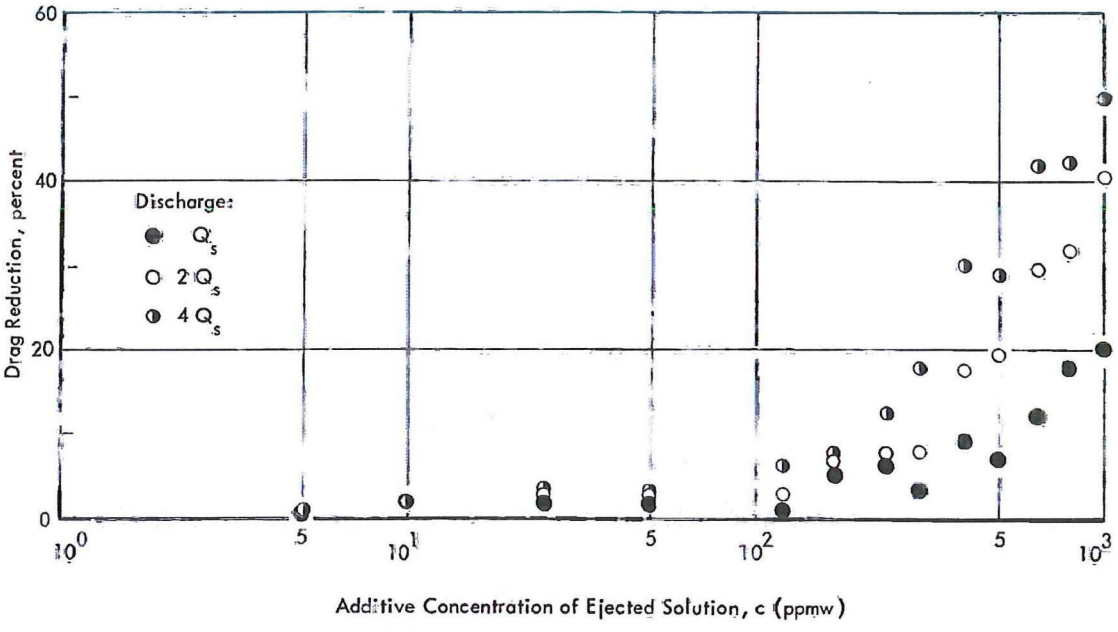


FIGURE 6 - DRAG REDUCTION BY EJECTING ADDITIVE SOLUTIONS INTO A PURE-WATER BOUNDARY LAYER OF A ROUGH SURFACE (GLASS BEADS, SLOT OPENING 0.022 INCHES)

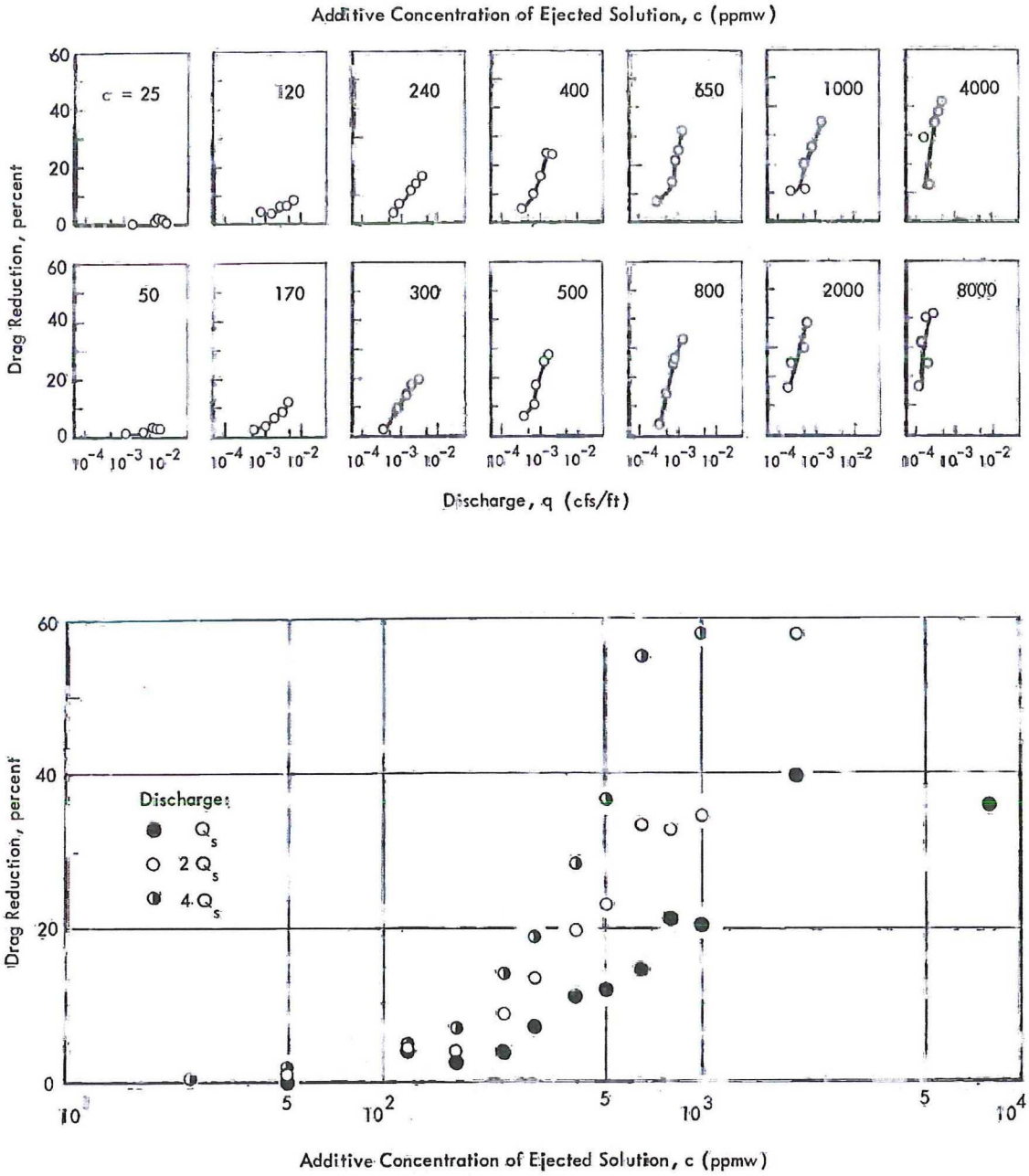


FIGURE 7 – DRAG REDUCTION BY EJECTING ADDITIVE SOLUTIONS INTO A PURE-WATER BOUNDARY LAYER OF A ROUGH SURFACE (RUBBER MATS, SLOT OPENING 0.022 INCHES)

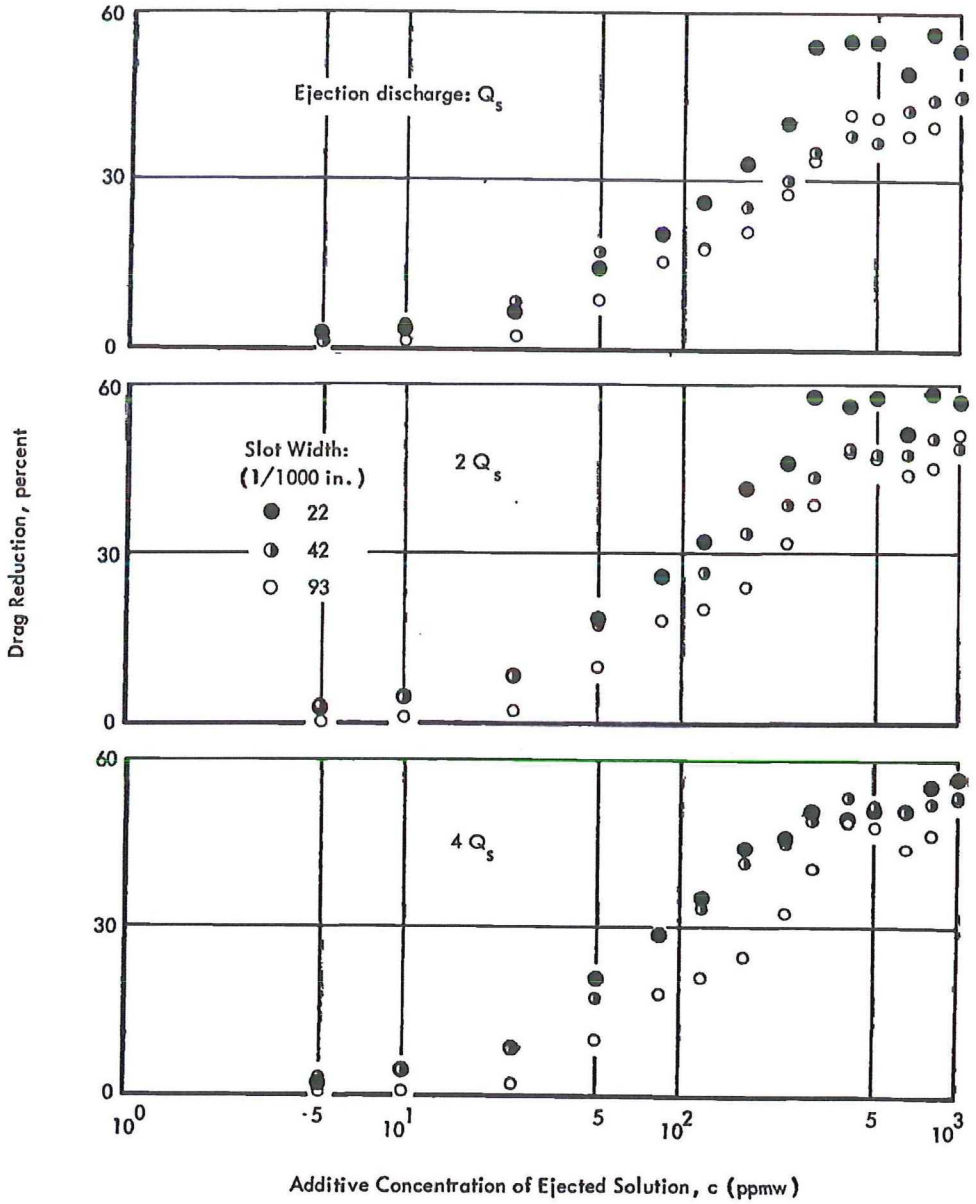


FIGURE 8 - DRAG REDUCTION BY EJECTED ADDITIVE SOLUTIONS OVER A SMOOTH BOUNDARY

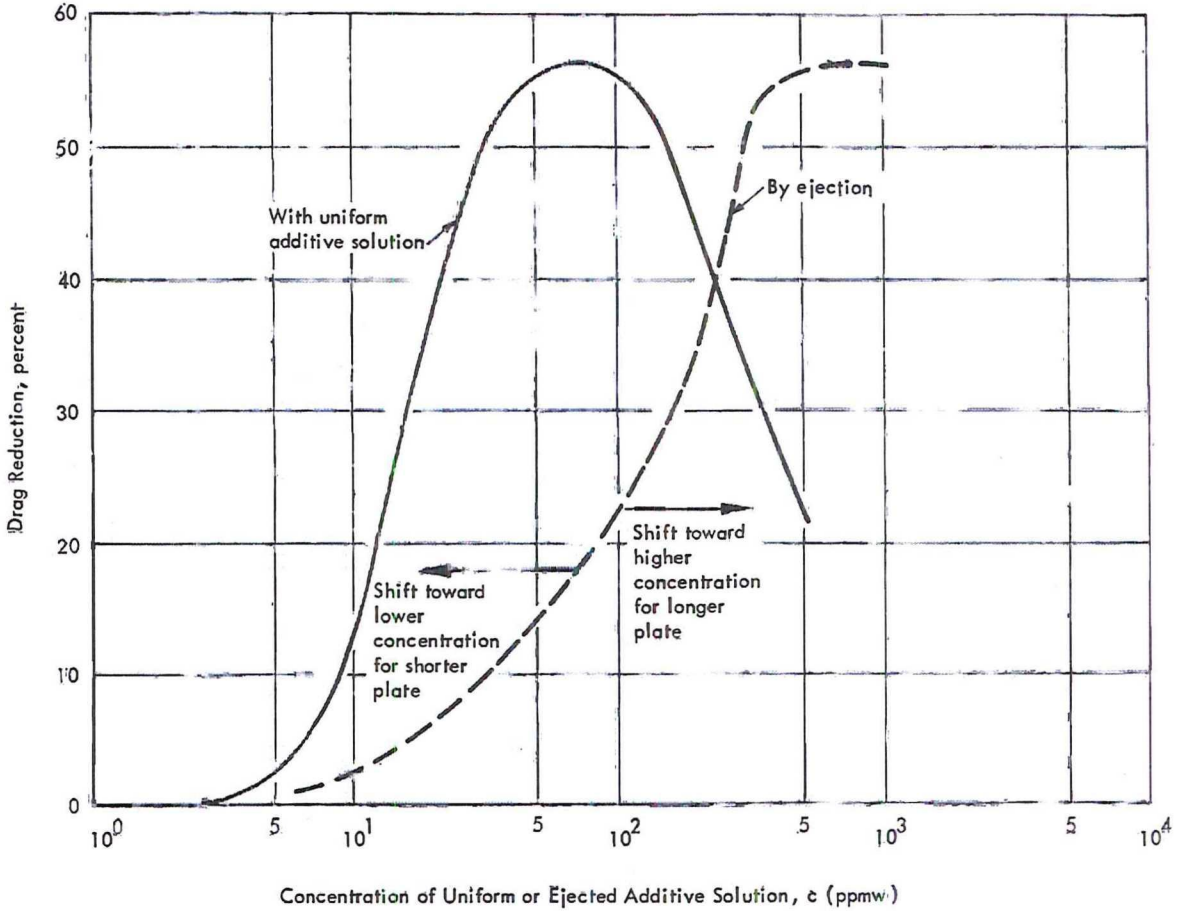


FIGURE 9 - TYPICAL DRAG-REDUCTION CURVE OF A PLANE BOUNDARY WITH UNIFORM ADDITIVE SOLUTION OR BY EJECTION

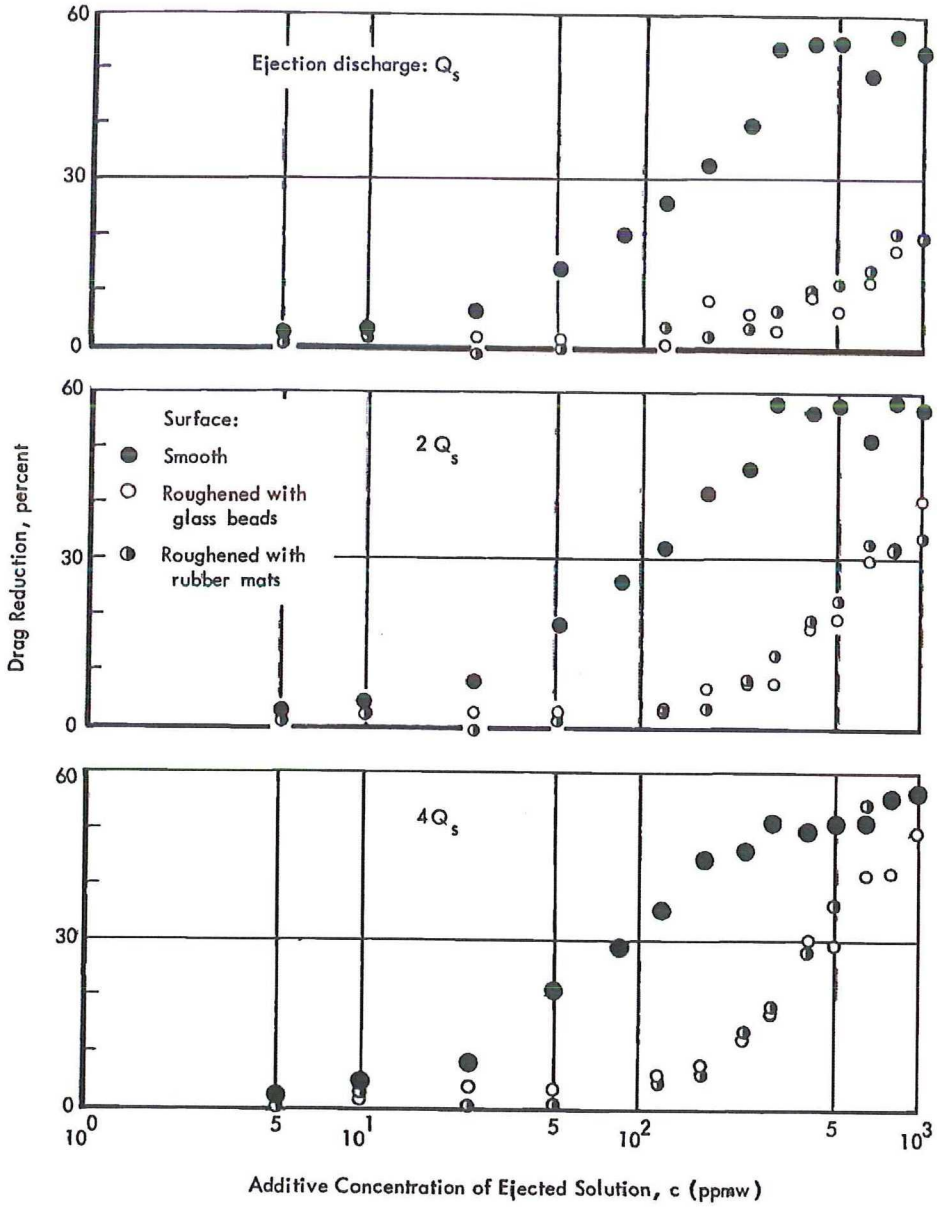


FIGURE10- DRAG REDUCTION BY EJECTING ADDITIVE SOLUTIONS OVER A ROUGH BOUNDARY

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Dr. H. Cohen
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13. ABSTRACT

Drag reduction caused by ejecting additive solutions from a slot into a pure-water boundary layer on a flat plate has been systematically studied. Results include drag measurements for a plane boundary, smooth and rough, with various openings of the slot and with various concentrations and discharges of the ejected additive solution. Conclusions have been drawn on the additive requirement in external flows and on the ejection technique for an optimum drag reduction.

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