Engineering Notes

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Drag Reduction by Polymer Diffusion at High Reynolds Numbers

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Introduction

SIGNIFICANT research efforts have been devoted to the evaluation of polymer requirements for efficient drag reduction by polymer ejection into a pure-water boundary layer at high Reynolds numbers. In a recent paper[1] previous work was reviewed and original evidence given concerning: 1) the particular characteristics of the diffusion process for polymer additives ejected into a boundary layer without pressure gradient at a Reynolds number of 3.25×10^7, and 2) the dependency of the drag reduction efficiency on the wall polymer concentration at the trailing edge of a long flat plate. However, the diffusion and drag reduction data were limited to concentrations of POLYOX WSR 301 between 100 and 1000 ppm. Moreover, the data indicate that, for ejected polymer concentration exceeding 500 ppm, the drag reduction efficiency tends toward lower values. Some additional data thus were required to substantiate both the drag reduction correlation with trailing-edge concentration and the diffusion model. This Note deals with these two aspects of the problem.

Because of the difficulty of performing simultaneous drag reduction and diffusion measurements in the high-speed recirculating channel, additional tests were limited to drag reduction measurements for injections made at three different ejection stations, concentrations ranging from 10 to 5000 ppm, and ejection velocities v_i between 0.01 and 0.5 of the freestream velocity V. The data were analyzed using the empirical diffusion model described in Ref. 1.

Experimental

The experimental setup at Hydronautics, Inc. and the main characteristics of the flat plate have been described in Ref. 1. In the present experiments, the ejector was placed alternatively at three different locations: 0.23, 0.63, and 1.39 m, respectively, from the leading edge of the plate. A constant freestream velocity of 10.65 m/s was used throughout the tests. The Reynolds number Re, defined with the plate length $L = 3.05$ m and a viscosity of water equal to 0.765×10^{-6} m^2/s, corresponding to a water temperature of 32°C, was 4.25×10^7. The local Reynolds number at the ejection location closest to the leading edge, station 1, is 3.45×10^6. A fully developed turbulent boundary layer will thus exist at all three ejection locations.

The test fluids consist of variously concentrated aqueous solution of polyethylene oxide, POLYOX WSR 301, having a molecular weight of about 4×10^6. The polymer solutions were prepared by spreading the additive on the surface of warm water, about 75°C, along with gentle mixing provided by a large paddle. The solutions were left to stand for 24 h prior to the testing in order to assure their homogeneity. The total resistance of the plate was measured with two block gages. Their output was averaged over a 2-s period. Their standard deviation was in all cases less than 1% of the average value.

Results

The corrections to be made on the total drag measurements to account for all associated drag components other than frictional have been discussed in Ref. 1. The deduced friction drag coefficient without water or polymer ejection is in agreement with the usual semiempirical laws. The drag reduction efficiency was computed as described in Ref. 1, using the Prandlt-Schlichting law instead of the power law for the turbulent flow over the plate in the absence of ejection. Fig. 1 presents some typical results for ejection made at the first station. Interpolated values of the fractional drag reduction for constant ejection velocities have been plotted as a function of ejected concentration. Similar plots were obtained for other two ejection locations.[2]

Discussion of Results

In Fig. 2, the fractional drag reduction achieved by ejecting POLYOX solutions with concentrations c_i of 10, 25, 50, 100, 250, 500, 1000, 3000, and 5000 ppm, from the three ejection locations at five ejection velocities, is shown as a function of the trailing-edge concentration c_L computed from Ref. 1:

$$c_L = 10.79(v_i/V)^{1.74}[s/(L-l)]^{1.16}c_i^{2.16}$$

for

$$L-l > 7.2(v_i/V)^{1.5}sc_i$$

and

$$c_L = c_i$$

for

$$L-l < 7.2(v_i/V)^{1.5}sc_i$$

where l is the distance between the leading edge and the ejector, and s is the ejector opening.

Figure 2 indicates, in spite of some scatter, that, for ejected concentrations between 10 and 500 ppm and trailing-edge concentrations between 1 and 100 ppm, the drag reduction efficiencies are comparable to those obtained in pipe and external flows with homogeneous polymer solutions of bulk concentrations equal to the trailing-edge concentrations.[3] For ejected concentrations higher than 500 ppm, the drag reduction efficiency is significantly below the minimum drag reduction curve that can be drawn for lower concentrations. These results confirm and extend those given in Ref. 1, which

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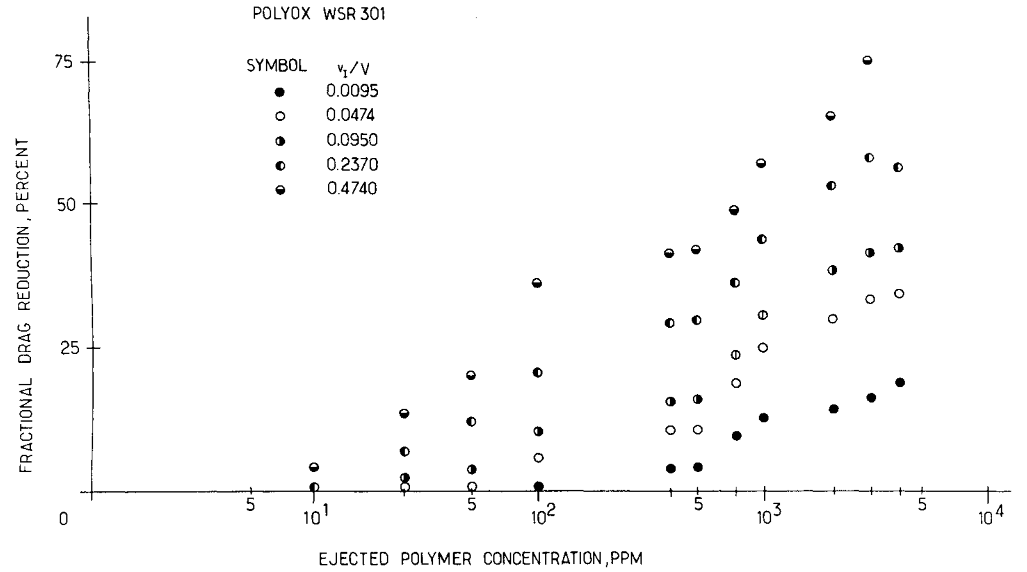

Fig. 1 Fractional drag reduction vs concentration of ejected polymer for constant ejection velocities.

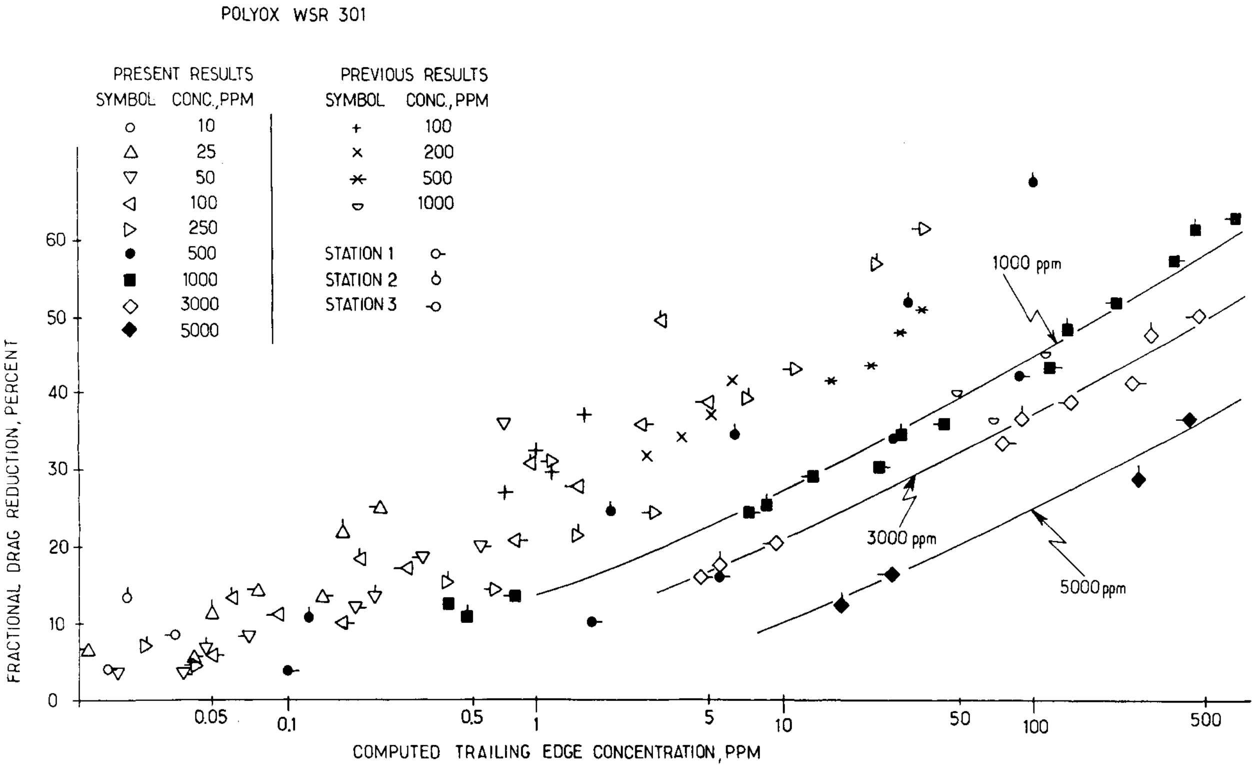

Fig. 2 Fractional drag reduction vs computed trailing-edge concentration—present and previous results.

showed that the efficiency was reduced for concentrations of 750 and 1000 ppm.

Analysis of the data shows the unnecessarily high consumption of polymer resulting from the ejection of solutions with too large polymer concentration. For the same fractional drag reduction, say 30%, the ejection of a 5000 ppm solution will require five times more polymer than the ejection of a solution of 100 ppm. Furthermore, for the same polymer consumption, a tenfold increase of the ejected concentration, from 500 to 5000 ppm, results in a *decrease* of the drag reduction efficiency from 35 to 12%, although the trailing-edge concentration increases, according to the diffusion model, from 6.6 to 17 ppm.

It thus seems that the earlier plot of Ref. 1 of drag reduction efficiency vs trailing-edge concentration permits a reasonably good estimate of polymer consumption requirements, provided that the ejected concentration is below 500 ppm. If the concentration is above this value, a considerable amount of polymer is ineffective for drag reduction purposes. A number of possible reasons exist to explain this behavior. It is known that, in homogeneous flow, drag reduction effectiveness of POLYOX declines for sufficiently large concentrations. In the case of high-concentration injection, therefore, a portion of the plate downstream of the injection slit will suffer reduced drag reduction. In addition, it may be that, for high enough concentrations, viscoelastic effects (jet swelling) at the ejector exit may enhance entrainement of the polymer solution by the outer boundary layer, causing a greater diffusion than was taken into account in the present analysis.

Conclusions

The following conclusions can be drawn:

1) The empirical diffusion model proposed by Fruman and Tulin[1] permits, in association with the drag reduction data presented here, a good estimate of the drag reduction efficiency that can be achieved by ejecting polymer solutions with concentrations equal to or less than 500 ppm.

2) For ejected concentrations larger than 500 ppm, the drag reduction efficiency is, for equal trailing-edge concentration, significantly reduced.

3) Use of large ejection concentrations results in unnecessarily large polymer consumptions.

4)For practical applications, distributed injections of low-concentration solutions will result in an overall better and more economical performance.

Acknowledgment

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[2] Wu, J., Fruman, D.H., and Tulin, M.P., "Drag Reduction Effectiveness of a Tangential Polymer Injection at High Reynolds Numbers," *Journal of Ship Research* (to be submitted for publication).

[3] Hoyt, J.W., "The Effects of Additives on Fluid Friction," *Journal of Basic Engineering,* Vol. 94, June 1972, pp. 258-285.

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