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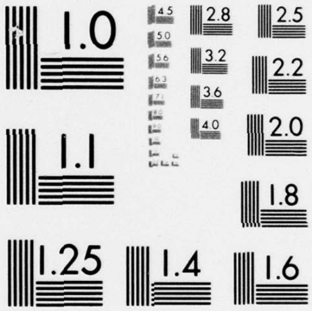
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FRICTIONAL DRAG REDUCTION - A LITERATURE SURVEY OF PROGRESS FROM SUMMER 1976 TO FALL 1977

by

Paul S. Granville

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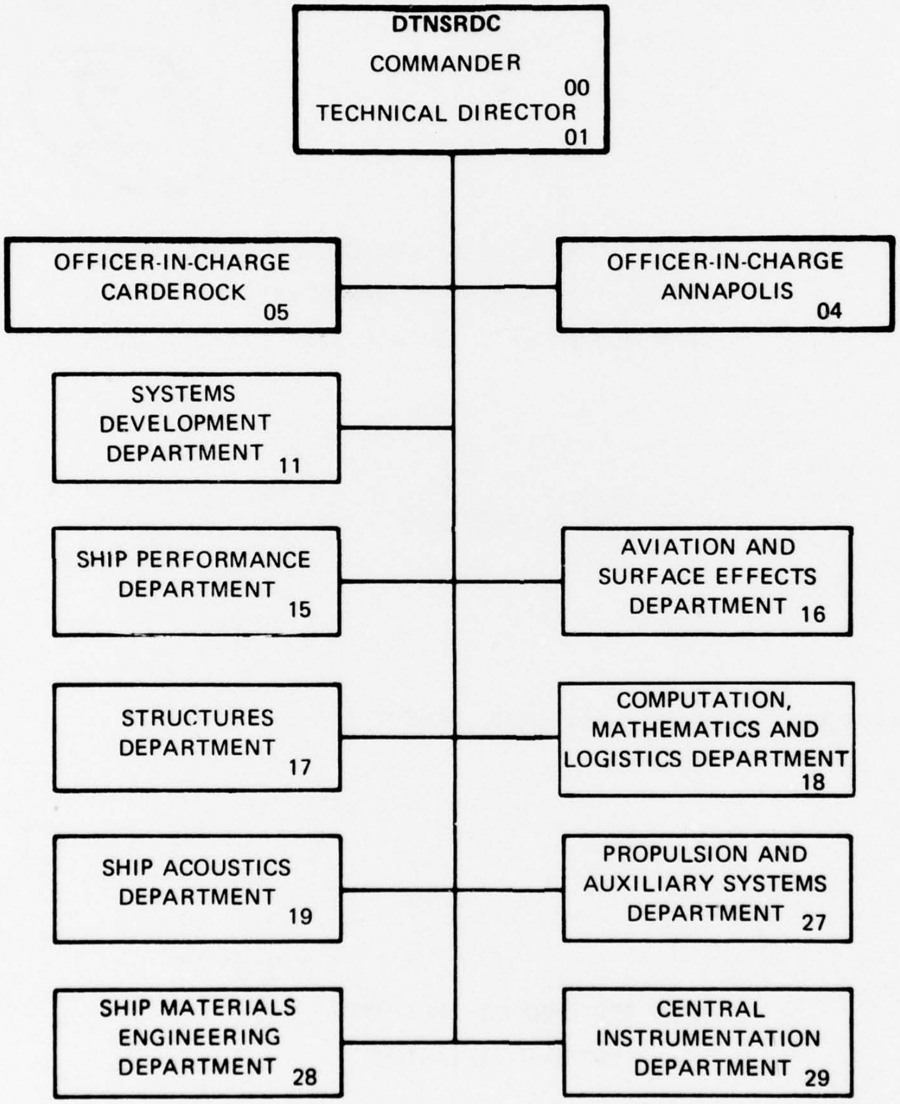

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FRICTIONAL DRAG REDUCTION - A LITERATURE SURVEY OF PROGRESS FROM SUMMER 1976 TO FALL 1977

Introduction

The reduction of turbulent skin friction has become increasingly necessary for aircraft and ships because of the markedly increased cost of fuel. Major efforts are being mounted by NASA to reduce the drag of airplanes (47)* of which turbulent skin friction is a major component. Much effort is being devoted to the possible use of compliant surfaces either passively or even actively by controlled oscillatory waves. Other methods are being considered such as corrugated surfaces and longitudinal grooves. For hydrodynamic applications, however, most research on drag reduction is still being devoted to polymer additives.

The proceedings of the 1976 Symposium on Structure of Turbulence and Drag has been published in Physics of Fluids, Vol. 20, No. 10, Part 2, October 1977 (11, 29, 31, 42, 45, 71, 74, 80, 82, 84, 85, 87, 91, 100, 101, 112, 113, 117, 118, 120, 126, 130).

A second international conference was held on drag reduction in 1977 at the University of Cambridge (9, 12, 13, 14, 20, 21, 39, 44, 51, 53, 56, 63, 64, 65, 81, 86, 90, 92, 97, 103, 105, 108, 111, 114, 123, 124, 125, 127, 129). Here too, the emphasis was on polymer additives with other methods playing a secondary role. Among these other methods were papers on stabilizing laminar boundary layers in water by heating the body surface (64, 97, 124). In this connection, there was also an AGARD conference on transition from laminar to turbulent flow (134, 135).

A literature review for 1975 to 1976 is provided by Hoyt (53) on polymeric drag reduction.

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* Numbers in parenthesis refer to items in the bibliography.

Progress in the reduction of turbulent skin friction is reviewed for the period, summer of 1976 to fall 1977, as a continuation of past surveys (38). A bibliography is presented which shows that polymer additives still dominate drag-reduction research. Significant highlights and interesting items are briefly mentioned.

Fundamentals

Although the similarity laws provide characterizations of the drag-reducing polymer solutions which are sufficient for engineering predictions, the need exists for physical explanations on a more fundamental level. Hinch (49), Lumley (74), and Landahl (71) are convinced that the extension of the polymer molecular coils under shear provides a physical presence sufficiently large to affect turbulent shear stress generation. The extended molecules then stabilize the momentary inflectional velocity profiles arising from the bursting process observed at the wall (43, 116).

An additional difficulty in controlled experiments with drag-reducing polymers is the mix of molecular weights present in commercially available supplies. Berman (10) and Berman and Yuen (12) have shown that the highest molecular weights predominate in drag-reducing effectiveness. Dschagarowa and Mennig (28) further demonstrate experimentally the predominant effect of high molecular weight and increased polymer coil dimensions in enhancing drag reduction.

An interesting experiment is described by Cowden et al. (19) wherein molecules of Polyox are subjected to an electric field with a consequent loss of drag-reducing effectiveness. This confirms an earlier view that the gels of Polyox provide drag reduction. The electric field then removes macroscopic gel particles from the boundary layer and hence a lesser drag reduction results.

Diffusion of Injected Polymer Solution

Applications of polymer technology to drag reduction of external boundary layers involve the injection and subsequent diffusion of concentrated polymer solutions from the wall. Latto and El Riedy (73) confirm previously-defined zones of polymer concentration profiles; an initial zone next to the wall through the laminar sublayer where the concentration is almost constant and the diffusion is slow; an intermediate layer through the buffer layer where diffusion is rapid; a transient zone where diffusion occurs at a more moderate rate through the rest of the boundary layer and a final zone where the polymer fills the boundary layer. The initial zone of very high concentration may actually result in a drag increase over this region due to the increased viscosity of polymer solution. It is concluded that multiple injection of less concentrated solutions may provide more drag reduction.

Wu et al. (127) reconfirm that drag reduction is governed by the concentration at the trailing edge of a body and that too great an initial concentration is less beneficial. Other studies of injected polymer solutions are given in (72, 110, and 121).

Applications

Efforts continue to apply polymer drag-reduction technology to engineering problems such as reducing the pressure losses in pipe flows. Methods have been devised to scale-up laboratory results in order to achieve more precise predictions (20, 39, 101). Zakin et al. (131) describe oil-water emulsions combined with drag-reducing polymers as an improved method of petroleum transport in long pipe lines. Sellin (102) investigates the economics of providing drag-reducing polymers to increase sewer capacity in lieu of new sewers. Shenoy (107) applies drag-reducing surfactants to hot-water heating systems to improve performance. More economical disposal of fly ash from power plants by pipe-line transport is investigated by Pollert (90) who adds polymers to fly ash-water mixtures. Dobrychenko et al. (25) consider the use of surfactants as drag-reducing agents in hydraulic applications because of lack of susceptibility to destruction by mechanical and chemical means.

Bilgen and Vasseur (14) analyze the possible gains in efficiency for hydraulic machines using drag-reducing polymers at the condition of maximum drag reduction. Further experimental studies on polymer injection on hydrofoils have been performed to ascertain optimal injectional flow rates on drag and lift (32, 109). Hoyt and Taylor (54) describe their latest work on the effect of polymers on waterjets issuing into the atmosphere. A simple method is proposed for predicting drag reduction on bodies in terms of form factors and equivalent flat plates (40).

Compliant Coatings

The development of passive compliant coatings to reduce turbulent skin friction is still in the research stages which is to say that no reliable method of designing or manufacturing coatings has been devised. It is not known what motions of a compliant coating can produce drag reduction. A successful coating does not seem to exist as yet. The problem may be considered in two stages: first to find out what motions produce drag reduction; secondly, to design and manufacture a flexible coating which will produce these motions under the stimulus of the turbulent pressure fluctuations from the boundary layer itself.

In order to produce controlled motions in a compliant coating to study drag reduction effects, Weinstein and Balasubramanian (125) have designed an electrostatically-driven surface which is to be tested in subsequent experiments.

Bushnell et al. (15) and Dinkelacker (24) describe the current situation of compliant coatings in considerable detail. Related papers are (4, 48, and 78).

Experiments using compliant coatings on rotating disks are described by Reed (96), Hansen and Hunston (46), and Roschke (99).

Romanenko (98) ascribes any drag reduction on a dolphin not to its compliant skin but to favorable pressure gradients and the accompanying laminar flow arising from the whipping of the tail to provide propulsion. For coasting dolphins, the flow is completely turbulent.

Kramer (69) is now working on a three-layer coating to delay transition from laminar to turbulent flow.

Theoretical investigations involving velocity perturbations due to compliant wall motions have been made by Tsahalis (119), Yang and Heller (128), and Zimmermann (132, 133). It is not certain that the consideration of velocity perturbation is the correct physical model to account for any possible drag reduction. Bushnell et al. (15) believe that compliant-wall drag reduction may result from an interference in the bursting cycle observed in turbulent flow next to the wall.

Laminar Flow Studies

Keeping the flow laminar in the boundary layer encompassing the surface of a body is a potent method of drag reduction for moderate Reynolds numbers. The object is to stabilize the laminar boundary layer by providing fuller velocity profiles. An incoming normal velocity through the body surface by distributed suction is one method for producing more stable velocity profiles. Kozlov and Tsyganyuk (68) describe experiments on a body of revolution which achieves extensive laminar flow by distributed suction. Pfenninger (88) summarizes past efforts, starting in 1949, in attaining laminar flow on aircraft wings by means of suction through narrow slots.

Another technique to achieve more stable velocity profiles is by heating the surfaces of water-immersed bodies (134, 135). The variation of water viscosity with temperature gives rise to more stable velocity profiles and consequently a greater extent of laminar flow. Reshotko (92) calculates the reduced drag of bodies with heated surfaces. Wazzan and Gazley (124) show analytically the combined effects of favorable pressure gradients and heated walls in providing more stable velocity profiles. King et al. (64) show that accelerated motions of a body contribute to the formation of more stable velocity profiles. However, the combined effects of acceleration, favorable pressure gradient, and heated walls are not linearly additive. The favorable effects of acceleration are reduced by the presence of the other two effects. Kosecoff et al. (67) show in their calculations that the destabilizing effects of surface roughness are increased by favorable pressure gradients and heated walls.

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