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INJECTION OF DRAG REDUCING ADDITIVES INTO TURBULENT WATER FLOWS

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This report summarizes the major results from a study where the basic goals were to determine the mechanism(s) by which drag-reducing polymer solutions modify the turbulent momentum and mass transport in wall bounded flows and to develop optimal methods for injecting these additives. These results have been published in ten technical reports, eleven journal articles, nine conference proceedings and six MS or PhD theses. Complete citations are given in the report.

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SUMMARY OF RESULTS

The basic goals of this project were to determine the mechanism(s) by which drag-reducing, polymer solutions modify the turbulent momentum transport in wall bounded flows and to develop optimal methods for injecting these additives into those flows. The purpose was to learn how to control and to manipulate wall turbulence and thereby develop faster, more energy efficient, and quieter submersible vehicles.

The results have been published in ten technical reports, eleven journal articles, nine conference proceedings and six MS or Ph D theses. The earliest version of the results and conclusions appears in a technical report while the papers often contain additional analysis and more reflective conclusions. In this summary, reference will be made to the papers and reports. In all cases the papers should be used for the final interpretation of the results. The reports usually contain more data and additional details of the experimental apparatus and procedures.

Effective location of polymer additives:

At the beginning and towards the conclusion of the project, results were obtained that strongly indicate that the additives must be in the buffer region of wall flows ($10 \leq y^+ \leq 100$) before they are effective in reducing drag. Here y^+ is the distance from the wall normalized with the wall shear velocity and kinematic viscosity. The journal article by Tiederman et al. (1985) shows that when the polymer additive is only in the linear sublayer ($y^+ < 10$) there is no drag reduction and no change in the wall-layer structure. The wall-layer structure changed and drag reduction occurred when the polymer solutions had migrated from the linear sublayer into the buffer region. Similarly, results in the journal article by Smith and Tiederman (1991) and in Report

PME-FM-90-1 show that drag reduction from a thread of concentrated polymer solution injected along the centerline of a pipe occurs only when low concentrations of polymer diffuse from the thread and are convected into the near-wall region. In these experiments the concentrated thread did not migrate into the wall region of $y^+ \leq 100$. However, the low concentrations of polymer solution detected at $y^+ = 50$ were sufficient to account fully for the measured reduction in drag.

Optimal wall injection:

Experiments designed to develop optimal methods for injecting polymer solutions through flush mounted wall slots are reported in Report PME-FM-84-1, in the conference paper by Walker, Tiederman and Luchik (1984) and in the journal article by Walker, Tiederman and Luchik (1986). For the range of slot geometries, injection flowrates and additive concentrations examined, drag reduction depended primarily upon the injection concentration and injection flow rate. The optimum occurred at a flow rate that was slightly larger than the flow rate in the undisturbed linear sublayer and at a concentration of 700 wppm of the additive which was the polyacrylamide, Separan AP-273.

These experiments also demonstrated that for additive concentrations below 3 wppm, drag reductions of 30% could be achieved in the relative large 6.0×57.5 cm two-dimensional channel. It is hypothesized that this occurred because the additive had attained an excellent conformation for drag reduction by the time it reached the locations in the flow field where this result occurred.

Development of experimental and data processing techniques:

Due to the viscoelastic nature of the drag-reducing polymer solutions, conventional velocity probes such as hot wires and Pitot tubes have decreased sensitivity and are very difficult, if not impossible, to calibrate. Similarly, the additional, unknown normal stresses make isokinetic sampling a qualitative rather than quantitative procedure for measuring additive concentration. For these reasons there were significant efforts to develop laser velocimeter procedures as well as optical methods for measuring additive concentration throughout the project. The paper by Luchik and Tiederman (1985) demonstrated that the spanwise length of a laser velocimeter probe volume has no effect on the velocity statistics if the turbulent flow is homogeneous in the spanwise direction and if the velocimeter is operated in the individual particle, counting mode. A laser induced fluorescence method for making real-time measurements of additive concentration along a line in the flow (usually perpendicular to the wall) is described in Report PME-FM-88-1 and in the paper by Walker and Tiederman (1989b). The combination of this laser induced fluorescence method with a single-component laser velocimeter to yield simultaneous measurement of velocity and concentration is described in Report PME-FM-88-2 and in the paper by Walker and Tiederman (1989a). This laser induced fluorescence method superceded a similar concentration measurement approach described in Reports PME-FM-86 and PME-FM-87-1 which depended upon having a stationary mean value from a laser beam parallel to the wall and in the direction of homogeneity. The results presented in Report PME-FM-87-1 and in the Midwestern Mechanics Conference paper by Walker and Tiederman (1987) showed the spanwise extent of the 10:1 aspect ratio channels was insufficient to yield the stationary output required.

Eulerian methods were also developed to measure the time scales and structure of the principal momentum transport event called a burst. These methods which are summarized in the conference proceedings by Tiederman (1990a) evolved from procedures described in the journal article by Luchik and Tiederman (1987) and Reports PME-FM-86 and PME-FM-87-1. Detection schemes that use Eulerian velocity information from a single point identify only a portion of the total burst event. This is usually some aspect of an ejection. From an Eulerian viewpoint, each burst may contain several ejections. The main concept in properly identifying the total burst event is to group ejection detections from the same burst into a single detection. This grouping can be done most reliably from semi-log plots of the probability distribution for the time interval between the trailing edge of one ejection and the leading edge of the next ejection. The subsequent average burst period has a range of thresholds over which the result is not a function of the threshold. Moreover, all of the one-component and two-component techniques tested yield the same burst period as the flow visualization results when the latter are available. For Newtonian, two-dimensional channel flows between Reynolds numbers (based on channel height) of 9,000 and 50,000 the average burst period, $\overline{T}_B$, is best scaled with the wall shear velocity and kinematic viscosity to yield $\overline{T}_B^+ = 90$.

These optical methods and burst detection schemes were used to study turbulent structure in: (1) homogeneous (well mixed) drag-reducing channel flows; (2) the initial mixing region downstream of a flush mounted additive injector and (3) drag-reducing boundary layers. In all cases the drag-reducing results were compared to Newtonian results obtained in the absence of polymer additive.

Drag reduction in homogeneous, well mixed channel flows:

Turbulent structure in well mixed, drag-reducing, two-dimensional channel flows are described in the journal articles by Luchik and Tiederman (1988) and Harder and Tiederman (1991), the conference proceedings by Tiederman (1990b) and in Reports PME-FM-85-1 and PME-FM-89-1. Luchik and Tiederman's (1988) study compared two drag-reducing flows with well mixed, homogeneous polymer concentrations of 1.3 and 2.1 wppm to a fully developed channel flow of water. The mean velocity profiles, root-mean-square velocity profiles and the distributions of the $\overline{uv}$ turbulent correlation confirm that the AP-273 additive modifies the buffer region of the flow. The principal influence of the additive is to damp fluctuations normal to the wall.

Structural results showed that the average burst period increases for the drag-reducing flows. When compared to a water flow at the same wall shear stress, this increase in the burst period was equal to the increase in the average spacing of near-wall, low-speed streaks. Conditionally averaged velocity signals at $y^+ = 30$ centered on the leading edge of a burst structure, as well as those centered on the trailing edge had the same general characteristics in all three flows indicating that the basic structure of the principal momentum transport event is the same in drag-reducing flows. However, it was clear that the lower threshold Reynolds stress motions were damped in the drag-reducing flows while the higher threshold events were not damped. In the buffer region this yields a larger mean velocity gradient with damped fluctuations normal to the wall and increased fluctuations in the streamwise directions. It was hypothesized that some strong, three-dimensional, turbulent motions are required to maintain polymer molecules in an extended conformation where they can produce a solution with rheological properties that damp the lower threshold turbulence and thereby reduce the viscous drag.

Harder and Tiederman (1991) used seven fully developed, low concentration, two-dimensional, drag-reducing channel flows to determine the effect of wall strain rate, polymer concentration and channel height upon drag reduction and turbulent structure. Water flows at equal wall shear stress and with Reynolds numbers from 14,430 to 34,640 were measured for comparison.

The results clearly showed that the drag reduction depends upon wall strain rate, average polymer concentration and channel height independently. Moreover for these well mixed flows of low-concentration Separan AP-273 solutions; the slope of the logarithmic region of the mean velocity profiles increases as drag reduction increases. Therefore scale-up techniques based on either constant slope or equal wall strain rate are not valid for this polymer-solvent combination.

Most of the turbulent structure depended only upon the level of drag reduction. For example the root-mean-square of the fluctuations in the streamwise velocity increased while the root-mean-square of the fluctuations in the wall normal velocity decreased with drag reduction. Production of the streamwise mean square fluctuations and production of the Reynolds shear stress decreased in the drag-reducing flows. Therefore, as suggested in the journal article by Walker and Tiederman (1990), it appears that the polymer solution inhibits the transfer of energy from the streamwise to the wall-normal velocity fluctuations. This could occur through inhibiting the

Newtonian transfer mechanism provided by the pressure-strain correlation.

In six of the drag-reducing flows, the sum of the mean viscous stress and the Reynolds stress was equal to the total shear stress. However, for the combination of highest concentration (5 wppm), smallest channel height (25 mm) and highest wall strain rate (4000 s^{-1}), the sum of the Reynolds and viscous stress was substantially lower than the total stress indicating the presence of a strong non-Newtonian effect.

In all of the drag-reducing flows, the correlation coefficient for uv decreased as the axes of principal stress for the Reynolds stresses rotated toward the streamwise and wall-normal directions. Moreover, as described in Report PME-FM-89-1, measurements of the average burst period confirmed that the ratio of the average burst period for a well-mixed drag-reducing flow to the average burst period for a water flow at equal shear stress increases with drag reduction in a manner similar to the increase in streak spacing.

Initial mixing from a flush-mounted wall injector:

Results that describe the momentum and mass transfer in the region immediately downstream of a flush-mounted wall injector appear in Report PME-FM-88-1, Report PME-FM-88-2, journal articles by Walker and Tiederman (1989a, 1989b and 1990) and the conference proceedings by Walker and Tiederman (1989). These extended and complemented earlier results reported in Report PME-FM-85-1 and the journal article by Walker et al. (1986).

The most graphic illustration of the mixing process is given by the time-resolved concentration profiles (see PME-FM-88-1 and Walker and Tiederman, 1989b) at five axial locations varying from 10 to 200 mm downstream of a flush-mounted injector.

Both dyed solutions of 700 wppm Separan AP-273 and dyed water were injected into a fully developed two-dimensional channel flow of water. The time-resolved concentration profiles show that high concentration fluid moves outward from the near-wall region in long filaments lifting away from the wall layer. For polymer injection this process is completely inhibited in the region from 25 to 50 mm downstream of the slot. Therefore the mixing process for the polymer solution required a longer streamwise distance than for water injection.

The high extensional viscosity of the polymer solution yielded a strong correlation between large instantaneous polymer concentrations and small wall-normal velocity fluctuations causing lower levels of turbulent mass transport. Profiles of the turbulent diffusivities for mass were essentially the same at $x = 25$ mm in the flow with water injection and at $x = 200$ mm in the flow with polymer injection. However the turbulent momentum transport was reduced significantly at $x = 200$ mm for the polymer injection causing the turbulent Schmidt number to be different for these two flows. For polymer injection the turbulent Schmidt number was about 0.5 at $x = 200$ mm while the turbulent Schmidt number was about 2 at $x = 25$ mm for water injection (see conference proceedings by Walker and Tiederman. 1989).

The two-component velocity measurements reported by Walker and Tiederman (1990) showed that the polymer injection increased the root-mean-square levels of the streamwise velocity fluctuations at all streamwise locations. The injection process also caused elevated levels of the root-mean-square of the wall-normal velocity and the turbulent shear stress at the measurement location closest to the slot. However, the polymer solution subsequently reduced these quantities significantly below the levels present in the water flow for $x > 50$ mm. The decreased magnitude of $-\overline{uv}$ resulted from both a decrease in v' and a decrease in the correlation between u and v.

The polymer injection reduced the production of $\overline{u^2}$ while the production of $\overline{uv}$ was not changed. The reduced levels of v' and uv' along with the increase of u' caused by the polmer solution indicates that the polymer may alter the transfer processes represented by the pressure-strain correlations. These correlations represent the transfer of energy from $\overline{u^2}$ to $\overline{v^2}$ and the principal source of destruction for $\overline{uv}$.

Streak spacing and burst rate results from dye-slot flow visualization were reported by Walker et al. (1986) for streamwise locations 175 mm and 1500 mm downstream of the polymer injection slot. At 175 mm, the polymer concentration in the wall layer was about 50 wppm while at $x = 1500$ mm the additive was completely dispersed to a concentration of 2.6 wppm.

The average streak spacing measurements were in excellent agreement with previous results[+] from pre-mixed homogeneous polymer solutions that show a linear increase of the average streak spacing as the percent drag reduction increases. However, consistent with the mixing results, there was a marked difference in the nature of the streaks for the two locations. Near the polymer injection slot, the streaks were 3 to 4 times longer with less small scale oscillation than the streaks at $x = 1500$ mm.

The general structure of the ejections and bursts also differed markedly in the two locations. Near the slot there were relatively long quiescent periods between bursts, no

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+ D.K. Oldaker and W.G. Tiederman, "Spatial structure of the viscous sublayer in drag-reducing channel flows," *Physics of Fluids, 20*, S133-S144.

high frequency activity during a burst and the physical size of the burst was relatively large. For these reasons the data for the high polymer concentration region could be analyzed on a burst by burst basis. The results showed an increase in the burst period compared to the burst period for a water flow at equal wall shear stress. This increase was larger than the corresponding increase in streak spacing. This result agreed with the near-slot burst measurements reported in the conference proceedings by Luchik and Tiederman (1984) and in the journal article by Tiederman et al. (1985). However it is different than the burst period results obtained in homogeneous, well-mixed flows of polymer solutions (see Luchik and Tiederman, 1988 and Harder and Tiederman, 1991). There appears to be differences in the turbulent wall-layer structure of drag-reducing polymer solutions very near an injection slot where there are instantaneously high concentrations of additive. This distinction was not appreciated in 1986 and the data at x = 1500 mm were reduced using an assumed value of the number of ejections per burst that is most likely too large.

Boundary layer experiments:

Reports PME-FM-90-2 and PME-FM-91-1, the conference proceedings by White and Tiederman (1990) and the journal article by Koskie and Tiederman (1991) describe both Newtonian and drag-reducing boundary layer experiments. White and Tiederman (1990) demonstrated that excellent, adverse pressure gradient, equilibrium boundary layers could be established using a flexible wall to adjust the pressure gradient for a boundary layer growing on a flat wall. Koskie modified White's boundary layer channel by decreasing the height (to increase wall strain rates) and by adding a flush-mounted wall injector. The initial drag-reducing boundary layer experiments were conducted in a zero pressure gradient boundary layer with an upstream injection of 1000 wppm solutions of Separan AP-273.

There were three major conclusions from the two-component velocity measurements reported by Koskie and Tiederman (1991). The first is that the wall shear stress in drag-reduced boundary layers can be determined from velocity measurements in the linear sublayer provided that the near-wall polymer concentration is low enough that the viscosity is the same as the viscosity of the solvent. Second, the sum of the viscous and Reynolds stresses in polymer drag-reduced boundary layers does not always account for the total shear stress in the region $6 \leq y^+ \leq 100$. In agreement with Harder and Tiederman's (1991) channel results, some additional stress which is due to the polymer solution must be present. Note that this additional stress occurs in the region where extensional motions are largest. Finally, scale-up procedures which assume a constant slope in the logarithmic region of the mean velocity profile cannot be used because the slope increases linearly with the percent drag reduction.

Drag reduction in adverse pressure gradient boundary layers will be investigated in a subsequent study.

Reprints of the referenced documents may be obtained from Professor W.G. Tiederman, School of Mechanical Engineering, Purdue University, West Lafayete, IN 47907-1288.

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GRADUATE STUDENT SUPERVISION

Degrees Granted

1. D.T. Walker, MSME, School of Mechanical Engineering, Purdue University, May 1985, Thesis title: Injection of Drag-Reducing Additives into Turbulent Channel Flows: Optimization and Modeling.

2. T.S. Luchik, Ph.D., School of Mechanical Engineering, Purdue University, August 1985, Thesis title: The Effect of Drag-Reducing Additives on the Turbulent Structure in Channel Flows.

3. D.T. Walker, Ph.D., School of Mechanical Engineering, Purdue University, December 1988, Thesis title: Turbulent Structure and Mass Transfer in a Channel Flow with Polymer Injection.

4. K.J. Harder, MSME, School of Mechanical Engineering, Purdue University, August 1989; Thesis title: Influence of Wall Strain Rate, Polymer Concentration and Channel Height Upon Drag Reduction and Turbulent Structure.

5. R.E. Smith, MSE, School of Mechanical Engineering, Purdue University, December 1989, Thesis title: Investigation into the Mechanism of Polymer Thread Drag Reduction.

6. J.B. White, MSE, School of Mechanical Engineering, Purdue University, December 1989, Thesis title: The Effect of Adverse Pressure Gradient on Turbulent Burst Structure in Low Reynolds Number Equilibrium Boundary Layers.

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