

## FLOW DEVELOPMENT AND DEGRADATION IN THE POLYMERIC AND MAXIMUM DRAG REDUCTION REGIMES

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### INTRODUCTION

Turbulent drag reduction, flow development, and degradation of aqueous solutions of two Polyoxes, P309 and N60K, was studied by axial pressure profile measurements in two smooth, segmented, pipes with electro-polished bores and respective (ID, L/D, segments) = (7.77 mm, 220, 7) and (4.58 mm, 180, 6). Each test pipe was placed in a single-pass progressive cavity pump-driven flow system fed from two 180 liter tanks that held premixed polymer solutions. The W309 Polyox, MW =  $11.4 \times 10^6$ , was studied at concentrations  $C = 0.1$  to 10 wppm in the 7.77 mm ID pipe at Reynolds numbers from 5000 to 140000 while the N60K Polyox, MW =  $3.2 \times 10^6$ , was studied at concentrations  $C = 1$  to 500 wppm in the 4.58 mm ID pipe at Reynolds numbers from 4000 to 65000.

In both pipes, friction factors for solvent, deionized water DW, adhered to the Prandtl-Karman law within  $\pm 0.2$   $1/\sqrt{f}$  units. For polymer solutions the flow enhancements aka “slip”  $S' = (1/\sqrt{f_p} - 1/\sqrt{f_n})_{Re\sqrt{f}}$  observed in both pipes varied over the entire possible range  $0 < S' < S'_{mdr}$ , from  $S' \sim 0$ , near onset on the Prandtl-Karman law (1)  $1/\sqrt{f} = 4.0 \log Re\sqrt{f} - 0.4$ , to  $S' \sim 17$ , close to the maximum drag reduction asymptote (2)  $1/\sqrt{f} = 19.0 \log Re\sqrt{f} - 32.4$ .

Turbulent drag reduction in pipes decreases with distance downstream [1, 2, 3], on account of polymer degradation, by midpoint-scission [4]. Degradation was sensitively detected in the present experiments as a bifurcation in the pressure drops measured between upstream (j) and downstream (k) segments of the test pipe at fixed flowrate and the severity of degradation was inferred from an estimate of the ratio of (still-active/original) polymer concentrations in the downstream segment.

### RESULTS

Both 7.77 mm ID and 4.58 mm ID pipes had square cut-off entrances and the average downstream distances of all pressure tap pairs j&k are tabulated below:

Taps	1&2	2&3	3&4	4&5	5&6	6&7
Pipe ID	L/D					
7.77 mm	22.7	57.9	93.1	128.3	163.6	198.8
4.58 mm	42.4	72.3	102.1	132.0	161.9	

Solvent friction factors at any fixed turbulent flowrate were constant to within 0.8% for all tap pairs in the 7.77 mm pipe and to within 1.2% for tap pairs in the 4.58 mm pipe, that is, their respective solvent flow development lengths were  $L/D < 22.7$  and  $L/D < 42.4$ . These accord with “entrance lengths”  $L_{e,n}/D \sim 25$  to 40 cited for turbulent Newtonian pipe flow [5].

Flow development in the 7.77 mm pipe for P309 solutions of  $C = 0.1$  to 10.0 wppm is depicted in Figures 1 and 2 by Cartesian plots of the observed flow enhancements  $S'$  vs  $L/D$  at each of two fixed flowrates,  $Re = 23500$  and 91000, respectively below and above the “falloff point” [1] beyond which degradation became significant.

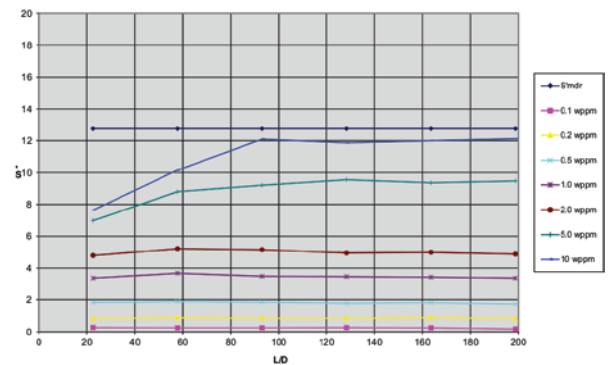


Figure 1. Flow Development at  $Re = 23500$ ; Pipe ID = 7.77 mm; Polymer = P309,  $C = 0.1$  to 10.0 wppm.  $S'_{mdr} = 12.8$  is maximum slip at this  $Re$ , calculated from (1) and (2).

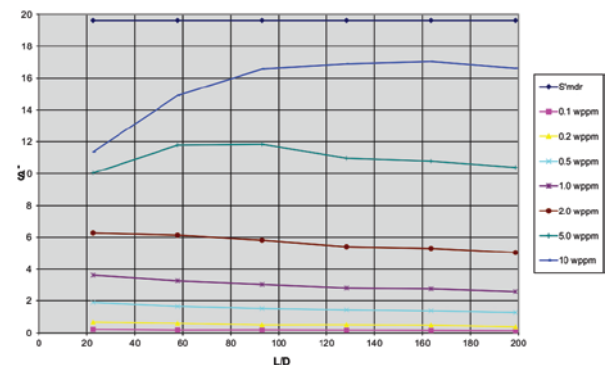


Figure 2. Flow Development at  $Re = 91000$ ; Pipe ID = 7.77 mm; Polymer = P309,  $C = 0.1$  to 10.0 wppm.  $S'_{mdr} = 19.6$  is maximum slip at this  $Re$ , calculated from (1) and (2).

In Figure 1 the three lowest  $C = 0.1, 0.2$  and  $0.5$  wppm each exhibit  $S'$  independent of  $L/D$  but increasing with increasing  $C$ , and this pattern persists, approximately, for the middle  $C = 1$  and  $2$  wppm too. However, for the two highest  $C = 5$  and  $10$  wppm,  $S'$  increases with increasing  $L/D$  at low  $L/D < 93$  and then becomes roughly constant for  $L/D > 93$ .

For  $C = 10$  wppm, specifically,  $S' = 8$  at  $L/D = 23$ , increases monotonically to  $S' = 12$  at  $L/D = 93$  and then remains constant at  $S' = 12 \sim S'_{\text{mdr}}$  for  $93 < L/D < 199$ . The foregoing show that, at the present fixed  $Re = 23500$ , flow development depends upon drag reduction. Solutions that induced  $S' < 5$ , say, required  $L/D < 22$ , akin to solvent, while solutions that induced  $S' > 5$ , took longer to develop, with one that attained  $S'_{\text{mdr}} \sim 12$  requiring  $L/D \sim 93$ .

In Figure 2 the three lowest  $C = 0.1, 0.2, 0.5$  wppm and the two middle  $C = 1, 2$  wppm each exhibit local  $S'$  decreasing perceptibly and monotonically with increasing  $L/D$ , while the average  $S'$  increases with increasing  $C$ . As examples,  $C = 0.5$  wppm shows  $S' = 1.9$  at  $L/D = 23$  decreasing to  $S' = 1.3$  at  $L/D = 199$ , while at the middling  $L/D = 93$ ,  $S' = 0.2$  for  $C = 0.1$  wppm increases monotonically to  $S' = 5.8$  for  $C = 2$  wppm. For the two highest  $C = 5$  and  $10$  wppm,  $S'$  increases with increasing  $L/D$  past the lowest  $L/D = 23$ , attains a broad maximum, and then decreases with increasing  $L/D$  towards the highest  $L/D = 199$ . For  $C = 10$  wppm, specifically,  $S' = 11.4$  at  $L/D = 22$ , attains a maximum  $S' = 17.0$  at  $L/D = 164$ , and then decreases slightly to  $S' = 16.6$  at  $L/D = 199$ , with all  $S' < S'_{\text{mdr}} = 19.6$ . The foregoing reflect the superposition of polymer degradation, which appreciably diminishes  $S'$ , the more so further downstream, upon flow development at  $Re = 91000$ . Solutions that induced  $S' < 8$ , say, still developed akin to solvent, while those that induced  $S' > 8$  took longer. Both Figures 1 and 2 show that entrance lengths in the polymeric regime are akin to solvent,  $L_{e,p} \sim L_{e,n}$ , when  $(S'/S'_{\text{mdr}}) < 0.4$ .

Further facets of flow development and degradation in the polymeric and maximum drag reduction regimes are revealed by the detailed Prandtl-Karman friction factors of DW and selected polymer solutions plotted in Figures 3 and 4.

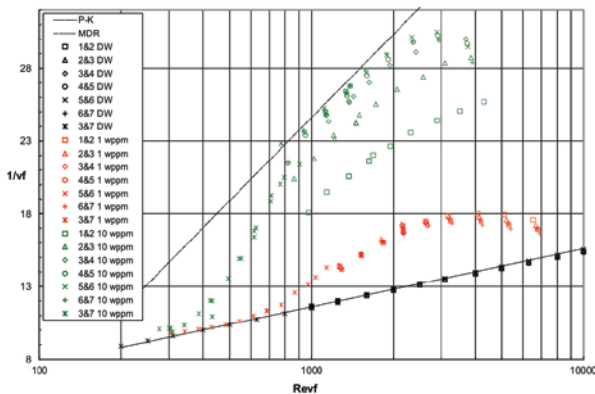


Figure 3. Friction factors for individual tap pairs (symbols). Pipe ID = 7.77 mm; Polymer = P309,  $C$  wppm = 0.0 (DW, black), 0.10 (red), 10.0 (green). P-K, MDR denote (1), (2).

Figure 3 shows that for DW (black), at any fixed  $Re\sqrt{f}$ , the individual friction factors from all tap pairs were virtually identical. Too, all DW friction factors adhered closely to the P-K law for  $1000 < Re\sqrt{f} < 10000$ . Data for  $C = 1$  wppm P309 (red) resemble a fountain, with an initial “jet”  $1250 < Re\sqrt{f} < 2500$ , wherein tap pairs cluster closely together, followed by a “spray”  $2500 < Re\sqrt{f} < 7000$ , wherein tap pairs separate, upstream higher than downstream, their separation increasing with increasing  $Re\sqrt{f}$ . The preceding define a characteristic “falloff point”,  $(Re\sqrt{f}^{\wedge}, S'^{\wedge}) = (2500, 4.3)$ , beyond which degradation becomes significant. Falloff parameters were used to infer apparent first order degradation rate constants, which

increased roughly linearly with increasing wall shear stress between the limits  $k_d 1/s = (0.5, 3.0)$  at  $Tw Pa = (50, 300)$ . For  $C = 10$  wppm P309 (green) over the range  $800 < Re\sqrt{f} < 2500$ , P-K friction factors for taps 1&2 ( $L/D = 23$ ) and 2&3 ( $L/D = 58$ ) lie respectively about 6 and 3 units of  $1/\sqrt{f}$  below all the other taps 3&4 to 6&7 ( $L/D = 93$  to 199), which latter cluster close to the MDR line (2). The flow development is concisely described by normalized flow enhancements  $(S'/S'_{\text{mdr}}) = (0.55 \pm 0.03, 0.78 \pm 0.02, 0.91 \pm 0.03, 0.95 \pm 0.03)$  at  $L/D = (23, 58, 93, 128$  to 199) that suggest an entrance length of  $L_{e,\text{mdr}}/D \sim 93$  at maximum drag reduction,  $(S'/S'_{\text{mdr}}) \rightarrow 1$ .

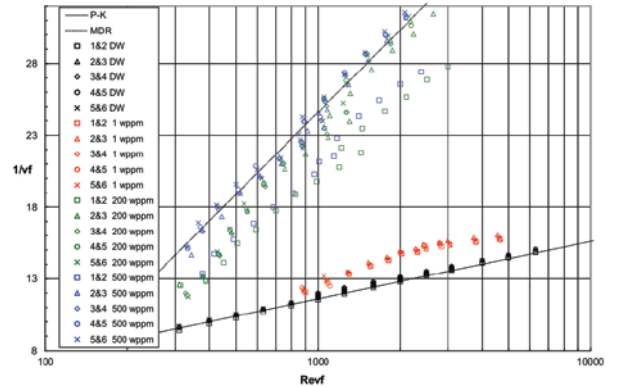


Figure 4. Friction factors for tap pairs (symbols). Pipe ID = 4.58 mm; Polymer = N60K,  $C$  wppm = 0.0 (DW, black), 1.0 (red), 200 (green), 500 (blue). P-K, MDR denote (1), (2).

In Figure 4 individual friction factors for DW (black) at any fixed  $Re\sqrt{f}$  were virtually identical, and all DW friction factors adhered to the P-K law for  $300 < Re\sqrt{f} < 6000$ . Data for  $C = 1$  wppm N60K (red) show tap pairs clustered together, akin to solvent, for  $900 < Re\sqrt{f} < 2500$ , with slight degradation apparent at higher flowrates. Detailed scrutiny provided a falloff point,  $(Re\sqrt{f}^{\wedge}, S'^{\wedge}) = (2500, 2.0)$  and apparent first order degradation rate constants that increased roughly linearly with increasing wall shear stress between limits  $k_d 1/s = (0.5, 4.5)$  at  $Tw Pa = (50, 450)$ . For  $C = 200$  wppm N60K (green) and  $C = 500$  wppm N60K (blue) over the range  $600 < Re\sqrt{f} < 2500$ , P-K friction factors for taps 1&2 ( $L/D = 42$ ) and 2&3 ( $L/D = 72$ ) lie respectively about 4 and 1.5 units of  $1/\sqrt{f}$  below all the other taps 3&4 to 5&6 ( $L/D = 102$  to 162), which latter cluster close to the MDR line (2). Normalized  $(S'/S'_{\text{mdr}}) = (0.70 \pm 0.05, 0.93 \pm 0.03, 0.97 \pm 0.03, 1.00 \pm 0.02)$  at  $L/D = (42, 72, 102, 132$  to 162) suggest an entrance length of  $L_{e,\text{mdr}}/D \sim 102$  at maximum drag reduction,  $(S'/S'_{\text{mdr}}) \rightarrow 1$ .

## REFERENCES

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