TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

9C-3

# TURBULENT PIPE FLOW MANIPULATION: SOME EXPERIMENTAL AND COMPUTATIONAL RESULTS FOR TANDEM MANIPULATOR RINGS

A. POLLARD[1], A.M. SAVILL[2] and H. THOMANN[3]
[1]Department of Mechanical Engineering
Queen's University at Kingston, Ontario K7L-3N6, CANADA
[2]Engineering Department
University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, ENGLAND

[3]Eidgenössiche Technische Hochschule
Sonnegstrasse 3, Zurich CH-8092, SWITZERLAND

## ABSTRACT

The effect on developing turbulent pipe flow of tandem blade manipulator devices has been investigated both experimentally and computationally. Wall pressure and mean axial velocity profiles have been obtained for six tandem manipulator configurations. Numerical calculations have been performed for one of these manipulator configurations using a finite volume method that incorporates a low Reynolds number model of turbulence. The results show clearly that no nett drag reduction is possible in this flow: local wall shear stress diminution is compensated by the device drag.

## INTRODUCTION

As a result of a concentrated research effort by a large number of research groups throughout the USA, Canada, Europe, Japan, and most recently China, it has been established that turbulent skin friction drag can be reduced through the use of surface modifications - particularly longitudinal riblets - and outer layer "manipulator" plates or aerofoils introduced into the flow itself [eg. see Wilkinson *et al.* (1987), Savill *et al.* (1988), Savill (1989a)]. In both cases apparent optimum devices parameters have been determined, these being related to the maximisation of a range of possible drag reduction mechanisms, and it has now been widely demonstrated that at least 6% nett drag reduction can be achieved through the application of riblets under a variety of flow conditions up to M=1.2 Sellin and Moses (1989). There is also some evidence that similar benefits may be attainable through the use of areofoil manipulators and that these can be constructively combined with riblets Savill (1989a), Sellin and Moses (1989). Both devices have already been tested on 3D bodies in both air and water, Sellin and Moses (1989), Coustols and Savill (1988), and riblets have also been used at full scale with apparent success in water, on rowing shells in the 1984 Olympics and 1988 Oxford-Cambridge boat race and the 1987 America's Cup winning yacht, Stars & Stripes (tank-testing on a 1/3 scale model of the previous winner, Australia II, having revealed total drag savings of 3% for the low wave-making conditions and the final rounds Sellin and Moses (1989), Anders *et al.* (1988) and flight tests on aircraft fuselages, wings and engine nacelles are presently underway. The concept of using such passive techniques to reduce surface drag is thus well established, at least for external boundary layer applications.

At the same time, initial attempts to model manipulated boundary layers with parabolic mixing length and k-$\epsilon$ models have led rapidly to more sophisticated treatments incorporating stress transport closures Savill (1989b). The latter were first used to successfully reproduce experimental results and have subsequently been used to predict the effect on such manipulated layers of streamline curvature, Savill (1988) and free-stream turbulence intensities/length scales, Savill (1987) representative of conditions within aeroengines. However to facilitate parametric computations leading to optimisation of manipulator configurations for practical flow conditions elliptic computations starting upstream of the device are required. Such a scheme, employing k-$\epsilon$, and 3- or 5-equation turbulence models has already been developed for ONERA-CERT, Coustols *et al.* (1987) and used to successfully predict the optimum height and spacing of tandem plate manipulators for low Re operating conditions. Further improvements are required to the near-wall modelling and to extend the calculations to curvilinear co-ordinates in order to handle areofoil devices, but there is clearly already some advantage to be gained from applying such computational procedures to internal flows where even the appropriate scaling of the device parameters is uncertain and the potential practical benefits have, therefore, yet to be established. Indeed similar computations are now being performed for riblets in both developing boundary layers, Sellin and Moses (1989) and fully developed channel flows, Coustols and Savill (1988).

Surprisingly, in view of the applications to pipelines and ducting, considerably less attention, until recently, had been paid to the possibility of applying such passive drag reduction devices in internal flows. However, performance levels similar to those found in external flows have now been recorded for riblets in a fully developed duct flow (preliminary), Lowson *et al.* (1989) and in a range of pipe flow experiments, Dinkelacker *et al.* (1987), Reidy and Anderson 1988), Rohr *et al.* (1989), Liu *et al.* (1989) even with two-phase flow, Sellin and Moses (1989). By contrast no nett benefits have been recorded with the limited number of manipulator configurations which have been tested in fully developed channel flow Prabhu *et al.* (1987) and in the more recent developing and fully developed pipe flow experiments conducted at ETH Zurich, Pompeo and Matievic (1987) and Laval University, Dickinson and Nguyen (1989). Moreover, initial low-Re k-$\epsilon$ elliptic computations by the present authors successfully post-dicted the ETH experimental results for single ring manipulators at $Re_D = 180,000$, Pollard *et al.* (1989a,b).

The purpose of the present paper is to present new low-Re k-$\epsilon$ predictions for tandem manipulator ring configurations and to compare these with the latest experimental data obtained at ETH Zurich.

## THE EXPERIMENTAL PROGRAMME

The experiments were conducted in a pipe 100mm in diameter (D=2R) and 6000mm long. Air was drawn into the pipe via a rounded nozzle inlet piece, before being directed through a flow straightening section. The pipe walls were instrumented with pressure taps. Various manipulator rings of different diameters were placed in the pipe at several stations downstream of the inlet (X) so as to vary the distance (h) from the wall ( *i.e.* h=R-r, where r is the outer radius of the manipulator ring). The manipulators were manufactured with a cord length of 20mm and a thickness tapering from 0.3mm at the leading edge to 0.15mm at the trailing edge. Each ring was supported by three equally spaced thin struts.

The data collected included mean axial wall pressure and radial mean velocity distributions measured at an axial location between that of the support vanes. For the case of the manipulators located at r/R=0.8, the height of the leading manipulator relative to the local boundary layer thickness ($h/\delta$) was 0.71 for X/D=5.0, 0.36 for X/D=18 and 0.24 for X/D=28. In the tandem configuration, with the manipulators located at r/R=0.8, the manipulators were placed 1.35D apart, and the leading edge of the first manipulator was located nominally at X/D=5, 18 and 28. Moreover, three other configurations were tested with nominal distance from the pipe entrance of X/D=18: r/R=0.8 and 0.9; r/R=0.9 and 0.8; and, with nominal distance X/D=18, r/R=0.8 and 0.8 but with the inter manipulator spacing decreased to 0.35D. In external flows, the optimum inter-manupulator spacing is about $s/\delta \approx 8$, Lynn *et al.* (1989); the current experiments are in the range of 9.6 $\rightarrow$ 3.2 for inter-manipulator spacing of 1.35D and 2.5 $\rightarrow$ 0.8 for inter-manipulator spacing of 0.35D. Thus, it can be expected that the small inter-manipulator spacing will be less advantageous than in the larger spacing case.

## THE CALCULATION METHODOLOGY

A finite-volume code employing a non-uniformly distributed staggered grid {up to (X)297 by (r)98} was used for the computations. The grid was refined near the wall, 40% of the points being below $y^+$=50 with the first at $y^+ \approx 1$. The manipulators were defined with 6 control volumes spanning their thickness, which was assumed constant at 0.3mm, and 20 control volumes along their length so that at both the leading and trailing edge the first grid points away from the devices were located at $x^+ \approx 1$ relative to its surface. (Note that all estimates in terms of wall units are based on the value of $u_\tau$ corresponding to the undisturbed fully developed pipe flow value). A version of the code had been validated previously for developing turbulent pipe flow, Pollard and Martinuzzi (1989), Martinuzzi and Pollard (1989). In view of recommendations resulting from these earlier computations the standard Lam and Bremhorst (1981) low-Re version of the k-$\epsilon$ model was employed.

The code utilised hybrid-differencing for the convective terms. Earlier studies (see, for example Martinuzzi and Pollard 1989) showed that for pipe flow, the use of such one-sided differencing schemes is acceptable. That is, the false-diffusion effects were found negligible. However the introduction of manipulators into a pipe also introduces a wake into the flow, the spreading of which may be over-estimated by the use of such a one-sided differencing scheme, Pollard and Siu (1982), but the effects of this behaviour can be reduced by using a fine enough grid so that the central difference scheme is recovered when the grid Peclet number is less than 2.

The wall boundary conditions used in the present calculations were as defined in Martinuzzi and Pollard (1989). The inlet conditions required considerable variation so as to achieve conformity with the mean axial velocity profiles for plane pipe flow. The "best" agreement was found when a log-law was specified from the wall to $y^+$=250 (a linear sublayer to $y^+$=11.5) together with a constant velocity between $y^+$=250 and the pipe centre-line. In view of the lack of any data, the inlet conditions for the turbulence kinetic energy and its dissipation rate were assigned uniform values across the pipe radius: $k = 0.002U_{avg}^2$ and $\epsilon = C_\mu k^{3/2}/0.02R$.

The particular turbulence model chosen accounted for near wall molecular viscosity effects by introducing a damping function ( *i.e.* $f_\mu$, which should vary between 0 and 1) into the calculation of the effective viscosity. This requires knowledge of the distance from a solid wall and was evaluated by taking the smallest distance between any point in the flow and the nearest solid boundary. In addition care was taken to ensure that the control volumes bordering the manipulators are suitably modified to account for the presence of the blockage.

## PRESENTATION OF RESULTS

The experimental wall pressure obtained by subtracting the plain pipe flow [without] from those obtained [with] manipulators is shown in Figure 1. The data are typical of those obtained regardless of manipulator configuration. It is clear that as the manipulators are located farther downstream from the pipe entrance that there is an indication that a negative pressure difference, implying drag reduction, may be achieved past X/D=60, the limit of the experimental rig. For the cases of manipulators located at different radii and smaller inter-manipulator spacing ($\Delta X/D$=0.35), data show an asymptotic behaviour to about $\Delta P \approx 1$ mm water, which is, within experimental error, equal to the device drag of the manipulators for that situation.

It is of interest to note that the parametric study conducted during the experiments revealed that when the manipulators were mounted within the initial developing boundary layer region the smallest device drag occurred for the two lowest height settings of h=0.36$\delta$ and h=0.71$\delta$. This is within the range of optimum heights reported for external flow operation and equivalent to 0.1 or 0.2R. Even then, only half the pressure drop due to the device drag was recovered within 200$\delta$ (equivalent to 60R) of the device, a similar recovery distance to that observed in channel experiments, Prabhu *et al.* (1987). In a more developed region, that is at X/D $\approx$ 28, the manipulator performance was independent of whether it was mounted at h=0.1, 0.2 or 0.3R, although it appeared that recovery was still continuing 60R downstream, the limit of the experimental rig.

Figure 2(a,b) displays the calculations for the pressure coefficient as a function of X/D. Shown in figure 2a are the experimental data for the plain pipe flow case, and the calculations for the plain pipe, single manipulator located at X/D=27.3 and the tandem arrangement. In figure 2b the single and tandem manipulator calculations are shown for the window $27 \leq X/D \leq 30$. Despite the slight over-prediction of the pressure in the pipe for $X/D \geq 40$, the pressure gradients are seen to be almost identical for all situations: the difference in magnitude being equal to the manipulator device drag.

The pipe wall friction coefficient for the tandem configuration only, shown in fig. 3, reflects the well documented reduction normally found in external flow situations. In these cases, the $C_f$ reduction is typically of order 10%, it is seen that for the tandem arrangement, $\Delta C_f/C_f \approx 0.09$, in accord with the external situation. It is seen also that the calculations asymptote to the Blasius value.

Although not shown, the calculations tend to overpredict the initial disturbance close behind the device probably due to the sharper leading edge than found in the experiments and also to the larger trailing edge thickness, Lemay *et al.* (1987) although a similar deficiency is apparent in k-$\epsilon$ computations for an external boundary layer Coustols *et al.* (1987), but overall the agreement is found to be respectable bearing in mind the experimental uncertainty, as indicated by the error bar on figure 1.

## CONCLUSION

The results of the present work can be summarised as follows:

1. New experimental data highlighting the effects of introducing tandem manipulators into turbulent developing and marginally developed pipe flow have been presented which indicate that drag reduction may be possible in developing pipe flow depending on the details and location of the manipulator device, and given sufficient development length. However, for the present cases the experimental longitudinal pressure gradients indicate little change in slope implying that any drag reduction, if any, is probably within the experimental error. The calculated pressure gradients were found to be in accord with the experimental data.

2. Numerical calculations employing a low-Reynolds number model of turbulence have been found to provide results that are in somewhat reasonable accord with the limited experimental data so far available.

3. Based on this, and the previously presented work on single manipulators in pipes, and duct flow, Prabhu *et al.* (1987), it would appear that the use of manipulators, when used alone in internal flow situations, is not a practically realisable drag reduction method.

## ACKNOWLEDGEMENTS

AP acknowledges the financial support of the Natural Science and Engineering Research Council of Canada, Queen's University Computing Centre and The School of Graduate Studies of Queen's University. AMS Acknowledges the support and interest of Rolls-Royce plc. The experimental work was performed by L. Pompeo, T. Matievic and B. Lineton, all students at ETH, Zurich.

## REFERENCES

J.B. Anders, M.J. Walsh and D.M. Bushnell (1988): The Fix for Tough Spots, Aerospace America, January, pp. 24-27.

E. Coustols, C. Tenaud and J. Cousteix (1987): Manipulation of turbulent boundary layers in zero pressure-gradient flows: detailed experiments and modelling. Proceedings 6th Symposium on Turbulent Shear Flows, Toulouse, Paper 11-5:1-5.

E. Coustols and A.M. Savill (1988): Resume of important new results presented at the Third Turbulent Drag Reduction Working Party, ONERA/Chatillon, September 29-30. Appl.Sci.Res. 46, pp. 183-196.

J. Dickinson and V. D. Nguyen (1989): As reported in: Report on 4th European Drag Reduction Working Party Meeting - to appear in ERCOFTAC Bulletin No. 4, December.

A. Dinkelacker, P. Nitshke-Dowsky and W.-E Reif (1987): On the possibility of drag reduction with the help of longitudinal ridges in the walls, Proceedings IUTAM Symposium on Turbulence Management and Relaminarisation, Bangalore, (Springer-Verlag) pp. 109-120.

C.K.G. Lam and K. Bremhorst (1981): A modified form of the k-$\epsilon$ model for predicting wall turbulence, ASME, Journal of Fluids Engineering, 103, pp. 456-460.

J. Lemay, A.M. Savill, J.-P. Bonnet and J. Delville, (1987): Some similarities between turbulent boundary layers manipulated by thin and thick plate manipulators, Proceedings 6th. Symposium on Turbulent Shear Flows, Toulouse, pp. 179-194, (Springer-Verlag).

K.N. Liu, C. Christodoulou, O. Riccius and D.D. Joseph (1989): Drag reduction in pipes lined with riblets. Proceedings, 2nd IUTAM Symposium on Structure of Turbulence and Drag Reduction. Zurich, Switzerland, July (Springer-Verlag).

M.V. Lowson, A.D. Jewson and J.H.J. Bates (1989): Drag reduction by riblets in a duct flow. Proceedings, IAHR International Conference DRAG REDUCTION 89 on Fundamentals and Applications of Drag Reduction Techniques: Additives and Passive Devices. Davos, Switzerland, July (Ellis Horwood).

T.B. Lynn, D.A. Gerich and D.W. Bechert (1989): LEBU-manipulated flat plate boundary layers - skin friction and device drag measured directly. Presented, IAHR International Conference DRAG REDUCTION 89 on Fundamentals and Applications of Drag Reduction Techniques: Additives and Passive Devices. Davos, Switzerland, July (Ellis Horwood) [Note, this paper was submitted too late to be included in the proceedings; contact DWB at DFVLR, Berlin].

R. Martinuzzi and A. Pollard (1989): A comparative study of turbulence models in predicting turbulent pipe flow. Part I: algebraic stress and k-$\epsilon$ models, AIAA Journal, 27, No. 1, pp. 29-36.

A. Pollard, A.M. Savill and H. Thomann (1989a): Turbulent pipe flow manipulation: some experimental and computational results for single manipulator rings, Journal of Applied Scientific Research, 46, No. 3, July, pp. 281- 290.

A. Pollard, A.M. Savill and H. Thomann (1989b): Turbulent pipe flow manipulation and modelling, Proceeding, IAHR International Conference DRAG REDUCTION 89 on the Fundamentals and Applications of Drag Reduction Techniques: Additives and Passive Devices. Davos, Switzerland, July, pp. 27-34, (Ellis Horwood).

A. Pollard and R. Martinuzzi (1989): A comparative study of turbulence models in predicting turbulent pipe flow. Part II: Reynolds stress and k-$\epsilon$ models, In press, AIAA Journal.

A. Pollard and A.L-W Siu (1982): The calculation of some laminar flows using various discretisation schemes, Computer Methods in Applied Mechanics and Engineering, 35, pp. 293-313.

L. Pompeo and T. Matievic (1987): Turbulenzbeeinflussung, Semesterarbeit in Fluiddynamik, ETH Zurich, Institut fur Aerodynamik Report WS 1986/87.

A. Prabhu, P. Kailas Nath, R.S. Kulkarni and R. Narashimha (1987): Blade manipulators in channel flows. Proceedings IUTAM Symposium on Turbulence Management and Relaminarisation. Bangalore, Springer-Verlag, pp. 97-108.

L.W. Reidy and G.W. Anderson (1988): Drag reduction for external and internal boundary layers using riblets and polymers, AIAA-88 0138.

J.J. Rohr, L.W. Reidy and G.W. Anderson (1989): An experimental investigation of the drag reducing benefits of riblets and polymers in pipes. Proceeding, IAHR International Conference DRAG REDUCTION 89 on the Fundamentals and Applications of Drag Reduction Techniques: Additives and Passive Devices. Davos, Switzerland, July (Ellis Horwood).

A.M. Savill (1987): Algebraic and Reynolds stress modelling of manipulated boundary layers including effect of free-stream turbulence. RAeS International Conference on Turbulent Drag Reduction by Passive Means, 1, pp. 89-143.

A.M. Savill (1988): Structural refinements to Reynolds stress closures for plane, manipulated and wake-boundary layer flows. Proceedings, 3rd International Symposium on Refined Flow Modelling and Turbulence Measurements, Tokyo (Universal Academy Press Inc.).

A.M. Savill (1989a): Recent developments in turbulent drag reduction by passive means. Review lecture paper for the 2nd. IUTAM Symposium on Structure of Turbulence and Drag Reduction, Zurich, Switzerland, July, to be published by Springer-Verlag.

A.M. Savill (1989b): Modelling approaches to drag reducing flows. Invited review article for publication in Progress in Aerospace Sciences.

A.M. Savill, T.V. Truong and I.L. Rhyming (1988): Turbulent drag reduction by passive means: a review and report on the first European drag reduction meeting. Journal de Mecanique 7 (4), pp. 353-378.

R.H.J. Sellin and R.T. Moses (ed) (1989): Drag reduction in Fluid Flows: Techniques for Friction Control, published for the International Association for Hydraulic Research, Ellis Horwood Ltd., Publishers.

S.P. Wilkinson, J.B. Anders, B.S. Lazos and D.M. Bushnell (1987): Turbulent drag reduction research at NASA Langley - progress and plans. Proc. RAeS International Conference on Turbulent Drag Reduction by Passive Means, pp. 1-31.

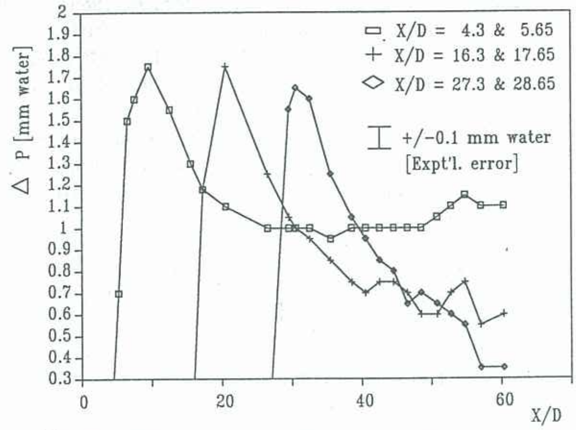

Figure 1: Experimental wall pressure differences with - withouttandem manipulators with leading edges located as noted, r/R=0.8, $Re_D$=180,000.

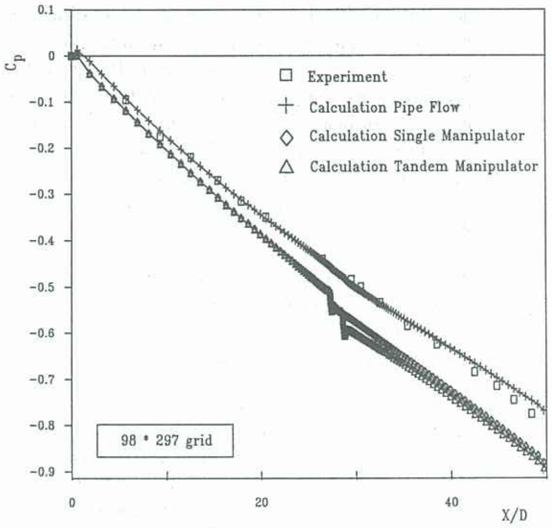

Figure 2a: $C_p$ *vs.* X/D for pipe flow, single and tandem manipulators, with leading edges at X/D = 27.3 and 28.65, r/R=0.8, $Re_D$=180,000.

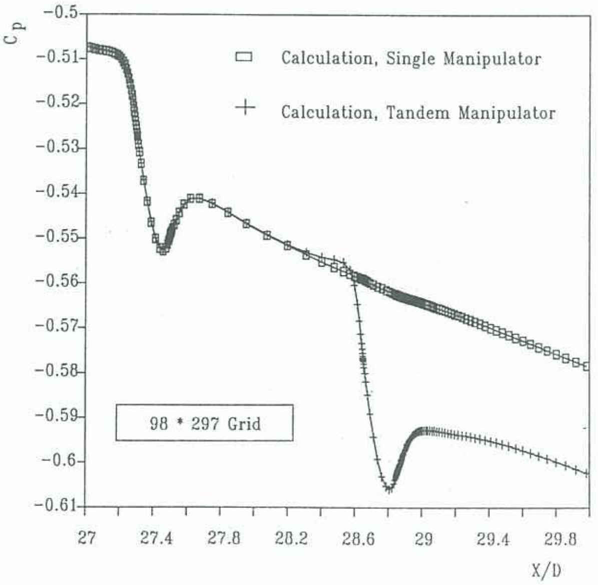

Figure 2b: Calculated $C_p$ *vs.* $27 \leq X/D \leq 30$ for single and tandem manipulators, with leading edges at X/D = 27.3 and 28.65, r/R=0.8, $Re_D$=180,000.

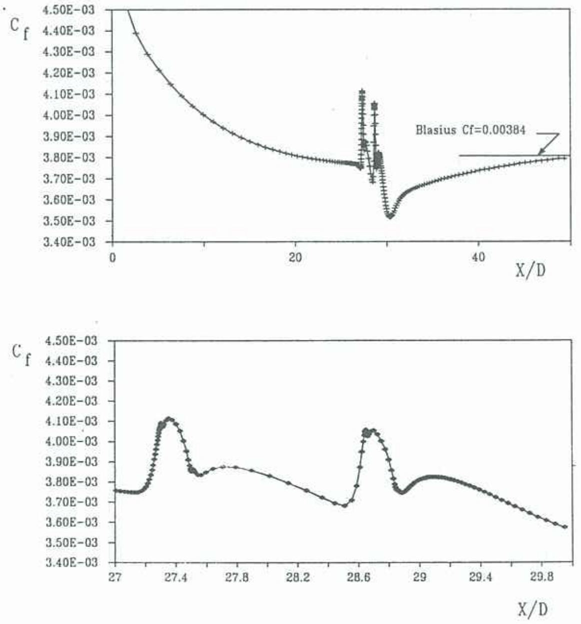

Figure 3: $C_f$ *vs.* X/D at pipe wall for tandem manipulators located at X/D = 27.3 and 28.65, r/R=0.8, $Re_D$=180,000. Lower portion of figure is expanded window $27 \leq X/D \leq 30$ of upper.