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NON-NEWTONIAN TURBULENT RECIRCULATING FLOWS

O. S. Castro
Departamento de Engenharia Mecânica
Instituto Superior de Engenharia do Porto
Porto
Portugal

P. M. Coelho and F. T. Pinho
Departamento de Engenharia Mecânica e Gestão Industrial
Faculdade de Engenharia da Universidade do Porto
Porto
Portugal

ABSTRACT

A Laser-Doppler anemometer and a pressure transducer were used to carry out detailed measurements of the mean and root mean square of the velocity and wall-pressure in an axisymmetric sudden expansion flow, with 0.4 and 0.5% by weight shear-thinning aqueous solutions of a low molecular weight polymer (6,000), after appropriate rheological characterisation. In spite of their very low molecular weight, these solutions still exhibited elastic effects through drag reduction of up to 35% relative to Newtonian turbulent pipe flow, as shown by Pereira (1993).

The results showed small variations of the recirculation bubble length with polymer concentration and Reynolds number and reductions of the normal Reynolds stresses in excess of 10%, especially in the tangential and radial directions. The reduction in normal Reynolds stresses within the shear layer, relative to a Newtonian flow, is an elongational elastic effect, which increases the recirculation bubble length, only when it is very intense, such as with high molecular weight polymers. Low molecular weight polymer solutions and inelastic fluids exhibit mean flow patterns similar to Newtonian fluids.

NOMENCLATURE

D - diameter of pipe downstream of sudden expansion
d - diameter of pipe upstream of sudden expansion
ER - expansion ratio
h - step height
K - consistency index in power law model
k - turbulent kinetic energy
L - recirculation bubble length
n - power law index in power law and Carreau viscosity models
R - radius of pipe downstream of sudden expansion
Re - Reynolds number
Re_a - Reynolds number based on wall viscosity in the upstream pipe
Re_{gen} - generalised Reynolds number (equation 4)
r - local radius
U - axial bulk velocity
U_{in} - axial bulk velocity at inlet
u - local axial mean velocity
u_o - axial centreline velocity
u' - local root mean square of axial velocity
v' - local root mean square of radial velocity
w' - local root mean square of tangential velocity
$\dot{\varepsilon}$ - dissipation rate of turbulence
$\dot{\gamma}$ - shear rate
λ - time constant of Carreau viscosity model
ρ - fluid density
μ - fluid viscosity
μ_a - viscosity at the wall in the upstream pipe
μ_o - zero shear-rate viscosity

Subscripts

ch - refers to a characteristic value
in - refers to characteristic values at the inlet pipe
max - refers to maximum values

INTRODUCTION

The wall-free shear layer resulting from the interaction of a jet and a recirculation bubble downstream of a sudden expansion flow makes this simple geometry suitable for investigation of turbulent flow characteristics. Furthermore, the requirements of a small rig and low quantities of fluid points out to its axisymmetric version as the most adequate for investigation of non-Newtonian fluids.

Newtonian sudden expansion flows have been thoroughly investigated in the past, in both the planar and axisymmetric geometries and though most of their main features are similar, the effect of pressure is different and results in particular in transitional asymmetric flow in the planar geometry, but not in the circular duct, as demonstrated by Cherdron et al (1978) and Iribarne et al (1972), respectively.

Early experimental research on Newtonian axisymmetric sudden expansion flows in the laminar and transitional flow regimes were reported by Macagno and Hung (1966), Iribarne et al (1972) and Back and Roschke (1972), who relied on photographic and visualisation techniques. They showed the direct linear dependence of eddy size on Reynolds number and the effect of expansion ratio. It was also clear from these works that the inlet condition strongly influenced the flow downstream of the expansion, with fully developed inlet flow leading to longer recirculations than uniform and almost uniform velocity profiles.

The works of Khezzar et al (1985), Durrett et al (1988), Dimaczek et al (1989) and Stieglmeier et al (1989) were aimed at investigating Newtonian turbulent flow characteristics and reported recirculation bubble sizes, normalised by the step height, of up to 24 for inlet Reynolds numbers of 900, decreasing to values between 8 and 10 for Reynolds number above 2,000. These authors showed, for various conditions, maximum normal Reynolds stresses occurring downstream of the expansion within an annular region centred about the expansion radius. It was also reported that the maximum values of the two transverse components of the Reynolds stresses occurred later than the maximum axial stress. A second region of high turbulence is the end of the reattachment zone because of normal strain-normal stress interaction and transport of turbulence by the mean flow, as reported before by Cherry *et al* (1984) for the planar geometry.

The literature on non-Newtonian expansion flows has been scarcer, especially regarding transitional and turbulent flow conditions. Halmos and Boger (1975) measured mean velocity and reattachment lengths in a 1:2 expansion by means of visualisation techniques for a purely viscous solution and generalised Reynolds numbers below 150. Eddy size was shown to increase with Reynolds number, as in a Newtonian fluid, and with shear-thinning. These results, and their Newtonian counterpart, were also numerically predicted by Halmos et al (1975) using a power law Ostwald-de Waele viscosity model. Perera and Walters (1977) were among the first to investigate the role of elasticity in their expansion/ contraction/ expansion laminar duct flow numerical simulations and predicted a reduction of the eddy size.

The recent experimental investigation of Newtonian, purely viscous and elastic shear-thinning sudden expansion flows of Pak et al (1990), who also used a visualisation technique, confirmed that elasticity reduced the recirculation bubble size in laminar flow but increased it in the turbulent regime. In the laminar regime the polymer concentration did not influence the eddy size of inelastic fluids, but for the viscoelastic case the bubble decreased with concentration, a clear sign of a stronger elastic effect. This work was further extended with elastic turbulent flows by Pak et al (1991), who carried out measurements of axial pressure drop and mean velocity for two different expansion ratios and showed that elasticity reduced the pressure loss relative to an inelastic fluid. Unfortunately, the authors did not report any Reynolds stresses so that a complete picture of the flow field did not emerge from those results.

In the confined baffle flow experiments of Pinho and Whitelaw (1991) with elastic shear-thinning fluids, a similar pattern of bubble size and pressure drop dependence on elasticity was observed and this was shown together with a damping of turbulence, especially in the radial and tangential components. Therefore, it is possible that a similar behaviour occurred in the Pak et al (1991) experiments.

It is clear from this review, that an extensive investigation of the turbulent and transitional sudden expansion flow characteristics with several non-Newtonian fluids of different rheology is required and this work is a contribution to such effort. Two different concentrations of an aqueous solution of a very low molecular weight polymer were selected and their mean and turbulent flow characteristics investigated in a sudden expansion flow.

Next, the fluid rheology, the flow configuration and instrumentation are described, and are followed by the presentation of the results and their discussion. This work ends with a summary of the main conclusions.

FLUID CHARACTERISTICS

The flow measurements were preceded by the selection of an appropriate shear-thinning fluid of low molecular weight, as described in Pereira (1993). The fluids selected were aqueous solutions of the low molecular weight (6,000 kg/kmole) methyl hydroxyl cellulose Tylose MH 10000K from Hoechst at concentrations of 0.4 and 0.5% by weight. The polymer was dissolved in Porto tap water and the rheological characterisation was carried out with the Physica double gap concentric cylinder rheometer, model MC100. The viscosity of the solutions at 25 °C is plotted in figure 1 together with the simplified Carreau model (eq. 1) resulting from a curve fitting to the experimental data, whose parameters are listed in table I. The solutions were rheologically considered as inelastic, with the ratio of the elastic to the viscous component of the complex viscosity in oscillatory flow of about 0.1 for frequencies of oscillation below 15 Hz, dropping to lower values at higher frequencies. In the creep tests the elastic deformation was always less than 1% of the total deformation.

However, the Tylose solutions were seen to be elastic, because they exhibited drag reduction in the turbulent pipe flow experiments described by Pereira and Pinho (1994), in spite of its rheology and of the low molecular weight of the polymer additives. These pipe flow measurements in a 26 mm diameter pipe showed drag reductions of up to 35% relative to water flow at the same Reynolds number based on wall viscosity. The measured friction coefficients were about half the maximum drag reduction predicted by Virk's asymptote, Virk (1975).

$$\mu = \mu_o \left[1 + (\lambda\dot{\gamma}_{ch})^2\right]^{\frac{n-1}{2}} \qquad (1)$$

TABLE I- PARAMETERS OF THE CARREAU MODEL FOR THE AQUEOUS SOLUTIONS OF TYLOSE MH 10000K (HOECHST) AT 25° C.

Solution	μ_0 [Pa.s]	λ [s]	n	$\dot{\gamma}$ [s^{-1}]
0.4% Tylose	0.0208	0.0047	0.725	6.1 a 4031
0.5% Tylose	0.0344	0.005	0.660	6.1 a 4031

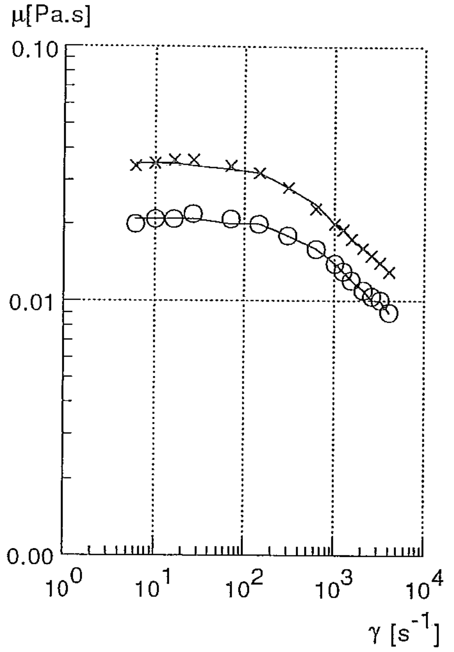

FIGURE 1- VISCOSITY OF THE 0.4%(O) AND 0.5%(x) TYLOSE SOLUTIONS AND CARREAU MODEL FITTING AT 25°C.

FLOW CONFIGURATION AND INSTRUMENTATION

The flow configuration, fully described in Castro (1994), consisted of a long 26 mm inside diameter vertical pipe ending at an abrupt expansion to a 40 mm diameter pipe, thus defining an expansion ratio of 1.538. A schematic representation of the test section is shown in figure 2 and includes the definition of the geometric parameters. Both pipes had a square outer cross section to reduce diffraction of light beams. The fluid circulated in a closed circuit pumped from a 100 litre tank through 90 inlet diameters of pipe prior to the transparent acrylic sudden expansion test section of 430 mm of length, and a further 700 mm down, back to the tank. A honeycomb was placed ninety diameters upstream of the expansion to help ensure a fully developed turbulent pipe flow at the inlet of the sudden expansion, as confirmed in the measurements of Pereira (1993). Eleven pressure taps were drilled on the enlarged pipe, within 14 diameters of the expansion, plus one pressure tap located just before the sudden expansion, to act as the reference location and a second one, further upstream, to help monitor the flow rate.

The pressure drop was measured with a P305D Valydine differential pressure transducer, model 30, which was interfaced with a 386 PC by a data acquisition Metrabyte DAS-8 board. The statistical quantities were calculated by a purpose-built software and the overall uncertainty of the pressure measurements was better than 1.2 Pa, which is about 1.6% and 5% for high and low pressure differences, respectively.

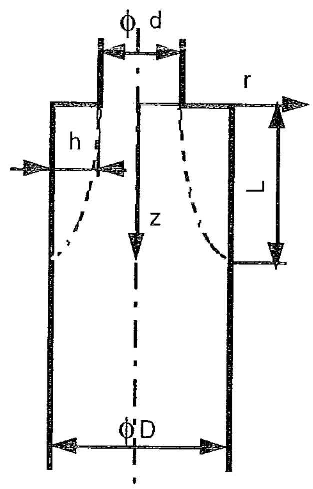

FIGURE 2- SCHEMATIC REPRESENTATION OF THE TEST SECTION AND ITS PARAMETERS.

A miniaturised fibre optic laser-Doppler velocimeter from INVENT, model DFLDA was used for the velocity measurements with a 30 mm probe mounted on the optical unit. Scattered light was collected in the forward direction by an avalanche photo diode and sent to a TSI 1990C counter for processing. The anemometer is fully described in Stieglmeier and Tropea (1992) and its main characteristics, of relevance to this work, are listed in table II. The output of the counter was connected to a computer, which provided the statistical quantities, via a DOSTEK 1400 A interface card. The velocimeter was mounted on a milling table with movement in the three co-ordinates and the maximum velocity and positional uncertainties at a 95% confidence level are as follows: 2% and 3.1% on axis to 2.8% and 7.1% in the high turbulence region downstream of the sudden expansion for the axial mean and rms velocities, respectively; 4.1% and 9.4% on axis and in the high turbulence region for both the radial and azimuthal rms velocity components; 200 μm for the x and y horizontal positioning of the control volume and 140 μm in the longitudinal positioning of the control volume. The effect of refraction of the laser beams at the curved optical boundaries was taken into account in the calculations of the measuring volume location and conversion factor, according to Durst et al (1981).

TABLE II - LASER-DOPPLER CHARACTERISTICS

Laser wavelength	827 nm
Laser power	100 mW
Measured half angle of beams in air	3.68
Measuring volume size in water (e^{-2} intensity)	
minor axis	37mm
major axis	550mm
Fringe spacing	6.44mm
Frequency shift	2.5 MHz

TABLE III- MAIN FLOW CHARACTERISTICS OF WATER AND TYLOSE FLOWS

Fluid	U_{in} [m/s]	Re	Re_{gen}	L/h	$\overline{u'^2_{max}}/U^2_{in}$	$\overline{w'^2_{max}}/U^2_{in}$	$\overline{v'^2_{max}}/U^2_{in}$	k_{max}/U^2_{in}
Water	6.09	178,000	178,000	8.67	0.0506	0.0326	0.0281	0.0542
0.4% Tyl	4.60	7,950	6,180	8.44	0.0551	0.0350	0.0252	0.0567
0.4% Tyl	6.45	12,150	9,070	8.00	0.0471	0.0280	0.0199	0.0476
0.5% Tyl	6.06	7,600	5,300	8.65	0.0534	0.0295	0.0206	0.0487

RESULTS AND DISCUSSION

In non-Newtonian fluid mechanics the definition of a Reynolds number is not straightforward as in classical fluid mechanics, because of the variation of viscosity with shear rate. In the particular case of the sudden expansion flow with fluids of constant viscosity, both the upstream diameter and step height have been used as characteristic lengths, with improved collapse of data, when the former is used in the Reynolds number definition and the latter is used to normalise the eddy length. For variable viscosity fluids it is also necessary to define an apparent viscosity, which should represent as faithfully as possible an average value, that is characteristic of the viscous processes taking place in the flow.

Viscosity plays a role in the dissipation of turbulent kinetic energy in turbulent flow and the following definition of viscosity was derived for power law fluids by Politis (1989), who considered the effect of the fluctuating velocities upon the average shear rate used to calculate the average viscosity.

$$\overline{\mu} = \rho^m K^{1-m} \dot{\varepsilon}^m \exp\left[m(m-1)\sigma^2/2\right] \quad (2)$$

K and n are the power law parameters, $m=(n-1)/(n+1)$, $\sigma^2= 0.45 \ln(L/\eta)$ where L and η represent the macro and micro scales of turbulence, respectively.

In spite of its sound physical basis, this expression is rather complex, requires an *a priori* detailed knowledge of the mean and turbulent flow field and consequently makes it difficult to compare different experiments; therefore, a different approach will be preferred here.

Removing the effect of the fluctuating velocity field, the characteristic shear rate in the mixing layer ($\dot{\gamma}_{ch}$), downstream of the sudden expansion, is on average proportional to the ratio of upstream mean velocity (U_{in}) to the step height (h):

$$\dot{\gamma}_{ch} = \frac{U_{in}}{h} = \frac{2U_{in}}{d(ER-1)} \quad (3)$$

Equation 3, together with the simplified Carreau model for the viscosity (equation 1), defines the average viscosity $\overline{\mu}$ to be used, with the upstream diameter d, in the Reynolds number (Re), throughout this paper.

Previous investigators have used a generalised Reynolds number (Re_{gen}) based on the upstream pipe and on the Ostwald de Waele power law parameters K and n.

$$Re_{gen} = \frac{\rho\, d^n U^{2-n}_{in}}{K} = \frac{\rho\, dU_{in}}{\mu_{in}(\dot{\gamma}_{in})} \quad (4)$$

The generalised Reynolds number definition can be coupled with any viscosity model, if a characteristic upstream pipe shear rate ($\dot{\gamma}_{in}$) of U_{in}/d is used. This definition will also be used here for comparison purposes, but coupled with the simplified Carreau viscosity model rather than the power law model.

Three flow conditions corresponding to the maximum flow rates for water, 0.4 and 0.5% by weight Tylose solutions were thoroughly measured and compared. In order to investigate the Reynolds number effect, the 0.4% solution was also measured at a lower flow rate corresponding to a similar Reynolds number as the 0.5% Tylose solution at the maximum flow rate. The main characteristics of these four tests are summarised in table III, which lists the upstream bulk velocity, the two flow Reynolds numbers, the normalised recirculation length, the normalised maximum normal Reynolds stresses and the normalised maximum turbulent kinetic energy. The turbulence data of table III are maximum turbulence values and do not necessarily occur at the same location within the flow.

To measure the recirculation bubble length the axial velocity was measured twice in a fine grid around the estimated location of the bubble end. The nodes of this grid were separated axially and radially by 3 and 0.2 mm, respectively and the overall uncertainty in the eddy size measurement, due to the fluctuating bubble and the mean velocity measurement accuracy is better than 5%.

Figure 3 compares well our normalised recirculation length for water with that of other researchers for different expansion ratios. It is clear that the variation of bubble length for Reynolds numbers above 5,000 is minimum. There is a small expansion ratio effect in the slightly lower normalised eddy sizes for the lower expansion ratios.

Figure 4 compares our non-Newtonian recirculation lengths with those from Pak et al (1990) as a function of the generalised Reynolds number defined in equation 4. All the data is plotted against this Reynolds number, except for the Separan solutions which uses the upstream wall Reynolds number (Re_a) based on the upstream wall viscosity (μ_a) calculated at the wall shear rate at the inlet pipe wall. Therefore, the two curves pertaining to Separan in figure 4 are shifted to the right, i.e., the upstream wall Reynolds number values are higher than the corresponding generalised Reynolds number values.

The Newtonian flow results of figure 3 show no major difference between ours and the measurements of Pak et al (1990), whereas in the shear-thinning plots of figure 4 the Tylose solutions exhibit slightly shorter eddy sizes than those of Pak et al's Carbopol solutions, and much smaller than their results for the strongly viscoelastic polyacrylamide solutions. Pak et al considered their Carbopol solutions as purely viscous based only on standard rheometrical data. They don't report neither drag reduction in turbulent pipe flow with their Carbopol solutions, nor any normal Reynolds stress measurements in the sudden expansion flow, which would give more insight of this flow.

For the Tylose solutions, on the contrary, in spite of its low molecular weight and the fact that the rheological measurements were unable to detect a sizeable elasticity, the turbulent pipe flow measurements of Pereira and Pinho (1994) showed drag reduction, an indication of a strong elongational elasticity effect. This is a clear evidence that standard rheometrical measurements are not enough to characterise the elastic behaviour of non-Newtonian solutions under turbulent flow conditions, such as drag reduction in pipe flow. This phenomena is a consequence of the increased elongational viscosity brought about by molecular stretching (Hinch (1977) and Kostic (1994)), whereas standard rheological measurements of elasticity are aimed at the behaviour of the solutions, with their molecules at conditions closer to equilibrium.

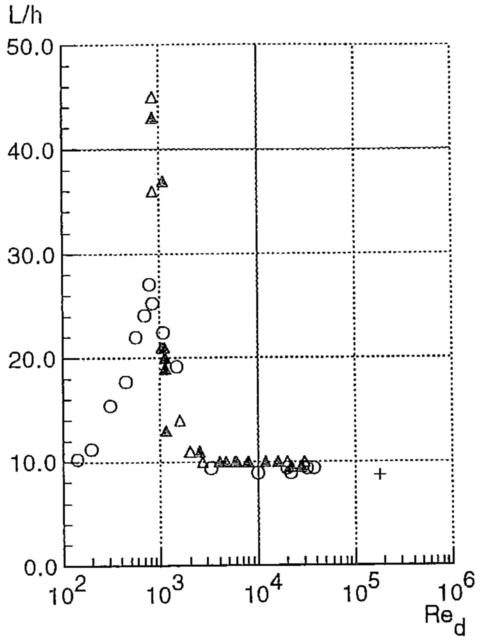

FIGURE 3- NORMALISED RECIRCULATION BUBBLE LENGTH FOR NEWTONIAN FLUIDS. O D/d= 1.749 KHEZZAR (1985); Δ D/d= 2.0 PAK ET AL (1990); ▲ D/d= 2.667 PAK ET AL (1990); + D/d= 1.538 PRESENT WORK.

Table III shows a slight reduction of eddy size with the addition of 0.4% Tylose to water at the maximum flow rate, accompanied by an increase in viscosity and a lower Reynolds number. As clearly depicted in figure 3, for Reynolds numbers below 6,000 to 8,000 a decrease in Reynolds number is accompanied by a lengthening of the recirculation bubble as one moves into the transitional regime, a behaviour also exhibited by the 0.4% Tylose solutions. Since the Reynolds number of the maximum bulk velocity 0.4% Tylose flow is still higher than the 8,000 limit this variation in eddy size between the water and the Tylose flow seems to result from a change in fluid rheology. However, adding more polymer to the 0.4% Tylose flow at maximum flow rate increases the bubble length and this can now result from two different effects acting in the same direction: a higher polymer concentration means a more elastic fluid which lengthens the bubble and a lower Reynolds number, in a range where transitional effects may start to be taking place, especially because non-Newtonian elastic fluids are known to widen the transitional flow regime range. At first sight these variations could be considered meaningless due to their small magnitude and in comparison to the measuring uncertainty, but Pinho and Whitelaw (1991) have also observed similar variations in their baffled flow experiments with the more elastic CMC solutions. They reported a reduction in eddy length by adding 0.1% CMC to water at Reynolds numbers above 20,000, followed by a recirculation bubble increase with further addition of polymer at Reynolds numbers well above those used here.

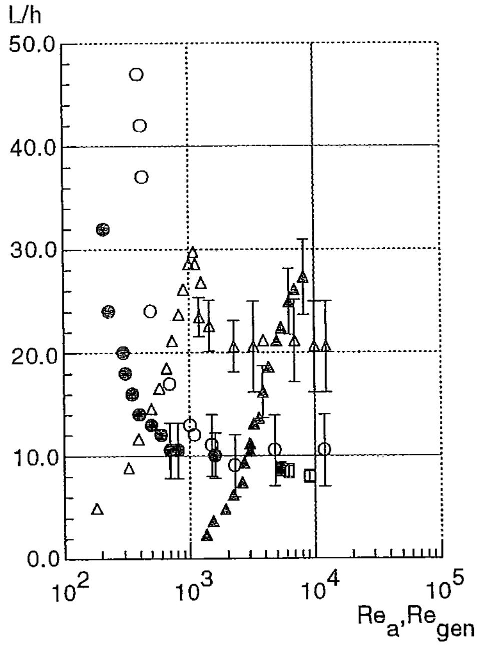

FIGURE 4- NORMALISED RECIRCULATION BUBBLE LENGTH FOR NON-NEWTONIAN FLUIDS (COMPARISON WITH PAK ET AL(1990)). D/d=2.667: O 5000 PPM CARBOPOL; ● 15000 PPM CARBOPOL. D/d=2.0: Δ 200 PPM SEPARAN; ▲ 1000 PPM SEPARAN. D/d=1.538: □ 0.4% TYLOSE ; ■ 0.5% TYLOSE.

The radial profiles of the axial mean velocity at several downstream stations of figures 5 b) to d) include Reynolds number and polymer concentration effects. The profiles are not very different from each other, but one can still see that within two upstream diameters of the expansion, the water and the high Reynolds number 0.4% Tylose solution have velocity profiles which are flatter and wider than those of the other two lower Reynolds number flows, as expected from their flatter inlet conditions, typical of higher Reynolds number pipe flow. This is confirmed in the plot of the longitudinal variation of the axial centreline velocity (u_o/U_{in}) of figure 5a), where the higher Reynolds number flows show lower values of u_o/U_{in} just downstream of the expansion. For the same reason, further downstream in the recovery region, the centreline velocity of the water and the high

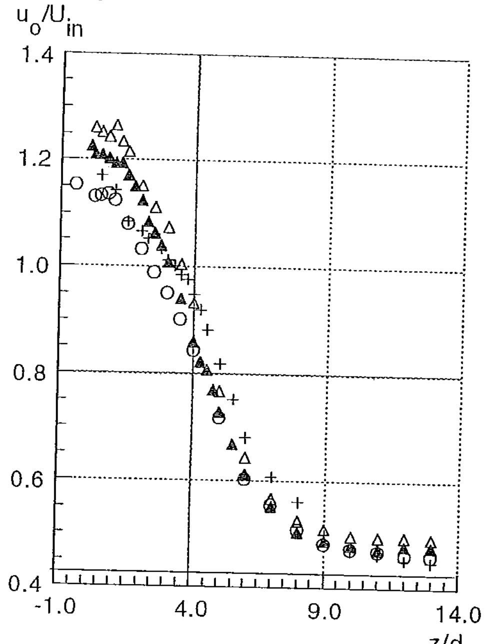

FIGURE 5a)- LONGITUDINAL VARIATION OF AXIAL VELOCITY. + WATER Re= 178,000; Δ 0.4% TYLOSE Re= 7,950; O 0.4% TYLOSE Re= 12,150; ▲ 0.5% TYLOSE Re=7,600.

Reynolds number flow of 0.4% Tylose show the tendency to a lower asymptotic value than the other two flows.

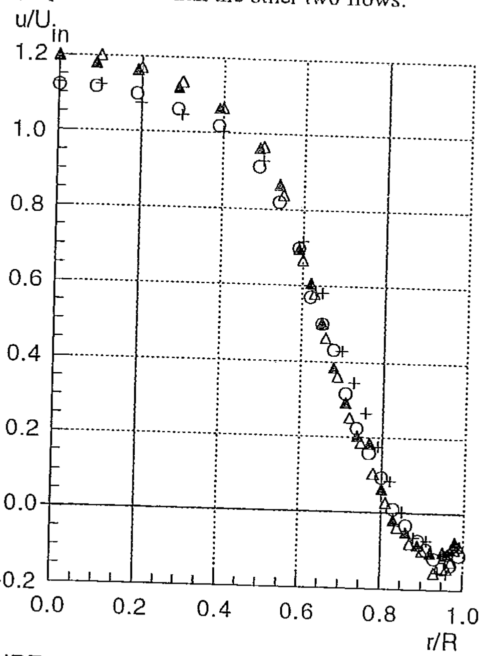

FIGURE 5b)- RADIAL PROFILES OF NORMALISED AXIAL VELOCITY AT z/d = 1. + WATER Re= 178,000; Δ 0.4% TYLOSE Re= 7,950; O 0.4% TYLOSE Re= 12,150; ▲ 0.5% TYLOSE Re=7,600.

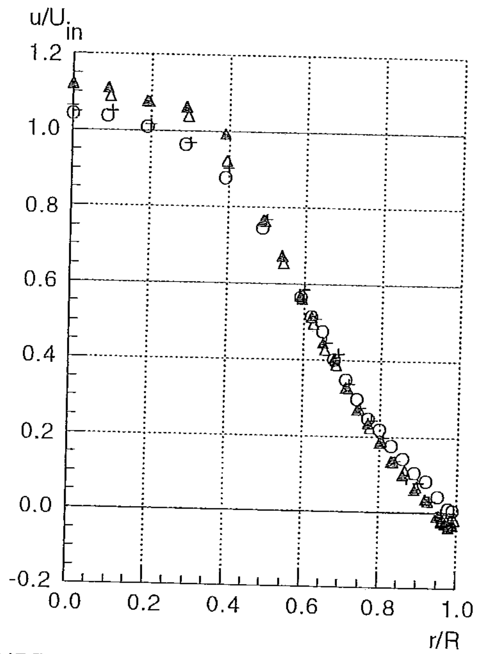

FIGURE 5c)- RADIAL PROFILES OF NORMALISED AXIAL VELOCITY AT z/d = 2. + WATER Re= 178,000; Δ 0.4% TYLOSE Re= 7,950; O 0.4% TYLOSE Re= 12,150; ▲ 0.5% TYLOSE Re=7,600.

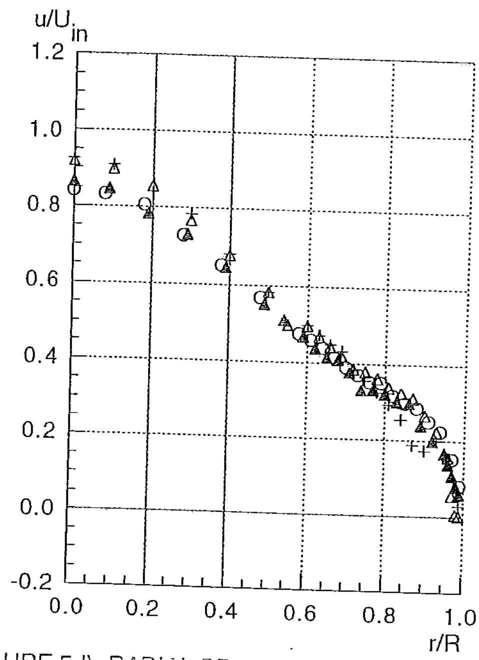

FIGURE 5d)- RADIAL PROFILES OF NORMALISED AXIAL VELOCITY AT z/d =4. + WATER Re= 178,000; Δ 0.4% TYLOSE Re= 7,950; O 0.4% TYLOSE Re= 12,150; ▲ 0.5% TYLOSE Re=7,600.

The maximum normal Reynolds stresses and turbulent kinetic energy for each flow condition are listed in table III and figures 6 to 8 show contour plots of the three normalised normal Reynolds stresses, which are also affected by polymer concentration and Reynolds number. Addition of 0.4% Tylose to water, for the maximum flow rate, reduces both the maximum values of the Reynolds stresses and the turbulence everywhere in the flow field, especially in the two transverse directions. The radial component of turbulence is the most affected with a decrease of the maximum value of up to 30%, followed by the tangential and axial components with reductions of up to 14 and 7 %, respectively. The turbulence is again raised with both a further addition of polymer concentration to 0.5% and a flow rate reduction with the 0.4% solution, because the Reynolds number decreases and the flow enters transitional behaviour. In the shear layer between the recirculation and the jet coming from the upstream pipe the increased turbulence is also a statistical quantity rather than true turbulence, because bimodal probability distribution functions of the velocity were observed, thus explaining the strong increase in maximum values.

Obviously, this is a low Reynolds number effect, which is accompanied by the above mentioned lengthening of the eddy size in spite of the increased'turbulence and is especially true close to the sudden expansion. Further downstream, the 0.5% Tylose flow has turbulence levels already similar to those of the 0.4% Tylose at a Reynolds number of 12,250, in spite of the earlier higher turbulence. On the contrary, at higher Reynolds numbers an increase in turbulence would mean improved momentum transfer and therefore a shorter recirculation.

The dampening of turbulence with the low elasticity Tylose solutions investigated here is less intense than that reported to occur with the more elastic CMC flow downstream of a confined baffle, especially in the axial and tangential directions, where maximum turbulence reductions of 20 and 40% were measured by Pinho and Whitelaw (1991) at a constant Reynolds number of 8,000 between Newtonian and the 0.2% CMC, and of 13% and 21% between the 0.2% and 0.4% CMC solutions, respectively.

The strong dampening of transverse turbulence shown here is another sign of elongational elasticity, which is known to affect mainly the radial and tangential directions, in both wall (Luchik and Tiederman (1988)) and wall-free turbulent flows (Berman and Tan(1985)). An especially remarkable effect of this behaviour is the comparison between the turbulence of the 7,700/ 7,900 Reynolds numbers flows of 0.4/ 0.5% Tylose solutions with that of the water flow: although the maximum axial turbulence of the shear-thinning fluids is higher than that for the water flow, the tangential and radial maximum values are not (figures 6 to 8). For this flow condition the dissipation of axial turbulence is faster with the shear-thinning fluids, which already shows less turbulence than the water flow downstream of z/d=5. In all the other comparisons that can be done between the different flow conditions, the variations of the maximum values of turbulence listed in table III are similar to the variations in the overall turbulent flow field, i.e., lower maximum values of turbulence are accompanied by lower turbulence at other equivalent locations. A reduction of Reynolds number at a constant Tylose concentration of 0.4% leads to higher turbulence and the increase in polymer concentration from 0.4 to 0.5% at a constant Reynolds number of 7,800 reduces turbulence. It is also important to remark that these observed variations of turbulence with Reynolds number and polymer concentration are consistent with the eddy size changes even though these are very small.

The differences between the mean flow data of the Tylose solutions and the measurements of Pak et al (1990) with Carbopol are small and, at first sight, have no significance, because of the uncertainties of the measurements of bubble length in both works and of the different inlet conditions; whereas they had a settling chamber followed by a contraction just upstream of the sudden expansion, in the present work there is a 90 diameter long pipe to ensure a fully developed turbulent inlet flow, Castro (1994). In the turbulent sudden expansion flow the recirculation length is mostly determined by the turbulence field. The perturbation to the flow brought about by the expansion is so large that the turbulence generated in the shear layer dominates the influence of the inlet condition. Therefore, it is not surprising to see that there are no major differences between our Newtonian measurements and those of Pak et al and other researchers, in spite of different inlet conditions.

This is why the mean flow behaviour of the Carbopol and Tylose solutions are similar and in order to get as strong an influence on the recirculation bubble length as that reported by Pak et al, a very elastic fluid that changes dramatically the turbulence pattern in the shear layer, such as polyacrylamide or polyethylene oxide, is required. On the contrary, if the effect of elasticity is to strongly enhance inlet condition differences this conclusion is wrong, so that further measurements with the same fluids under different upstream conditions would be necessary to clarify this point. However, the authors do not believe that this type of direct elastic effect on mean flow persists at such high Reynolds numbers although they are aware that they exist and are very strong in certain laminar flows with rapid changes of geometry (Boger and Walters (1994), Walters and Webster (1982)).

This work shows that the elastic effects present in the turbulent sudden expansion flow look similar to those present in turbulent pipe flow, i.e., a molecular stretching effect promoted by the turbulence dampens the turbulence within the shear layer; it does not come from the inlet pipe, except that the elasticity has also dampened the turbulence in the inlet flow field, but because its intensity is lower than within the shear layer, this upstream effect becomes almost irrelevant. Clearly, the longer recirculations of the polyacrylamide solutions, as compared to the Carbopol data of Pak et al and our Tylose measurements, must result from a strong dampening of turbulence after the sudden expansion, due to molecular stretching effects similar to those observed in turbulent pipe flow and more intense than measured with Tylose. This is not surprising, because polyacrylamide is known, together with polyethylene oxide, as one of the best available drag reducer polymers. Kostic (1994) has also reported that some fluids, such as Carbopol solutions, although exhibiting elasticity in rheological measurements, are known to behave in turbulent pipe flow as purely viscous fluids, showing no drag reduction. This is consistent with the sudden expansion hydrodynamics of the Car-

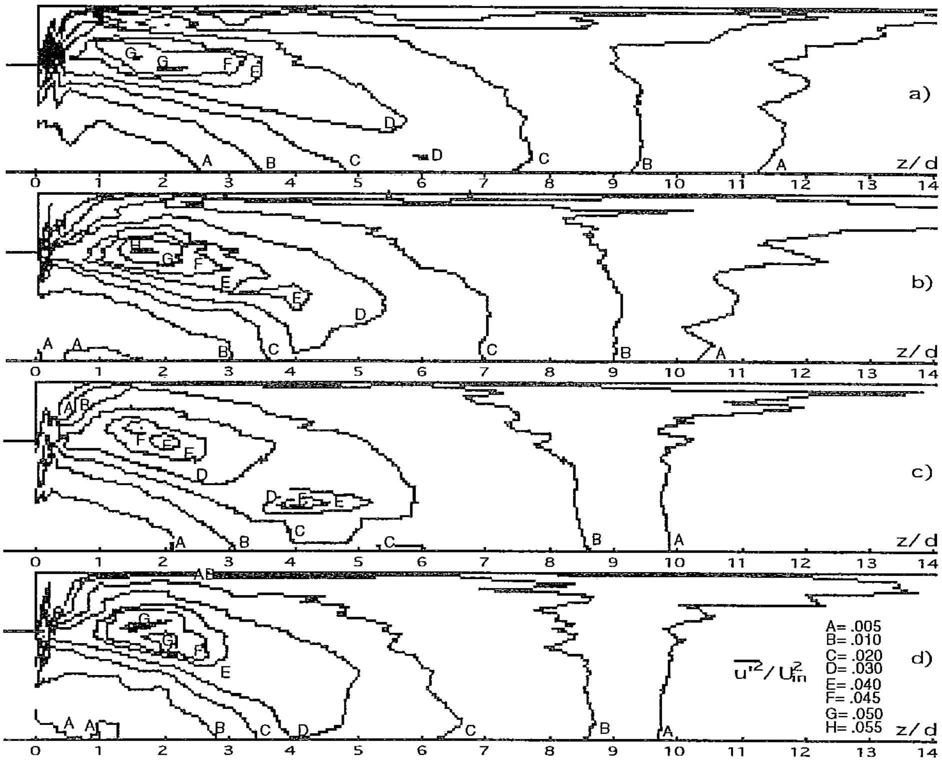

FIGURE 6- NORMALISED AXIAL NORMAL REYNOLDS STRESS. a)WATER Re= 178,000 b) 0.4% TYLOSE Re= 7,950 c) 0.4% TYLOSE Re= 12,150 d) 0.5% TYLOSE Re= 7,600.

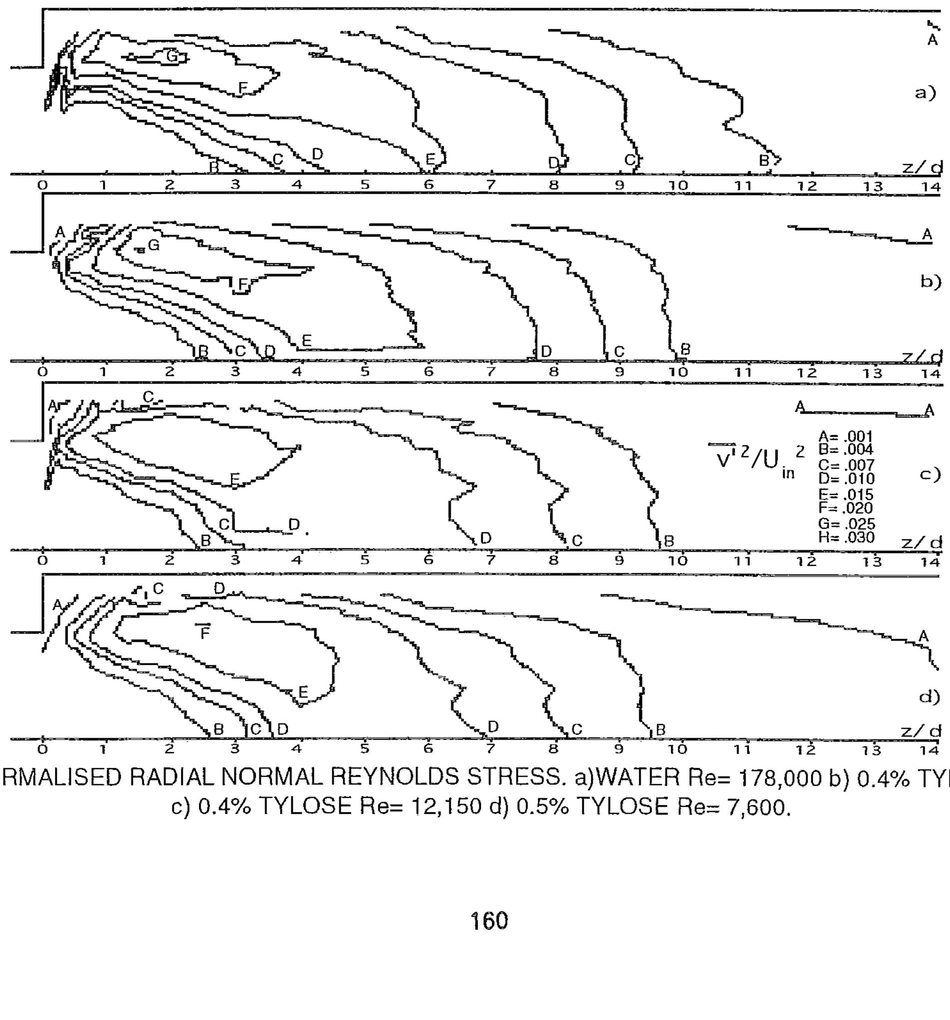

FIGURE 7- NORMALISED RADIAL NORMAL REYNOLDS STRESS. a)WATER Re= 178,000 b) 0.4% TYLOSE Re= 7,950 c) 0.4% TYLOSE Re= 12,150 d) 0.5% TYLOSE Re= 7,600.

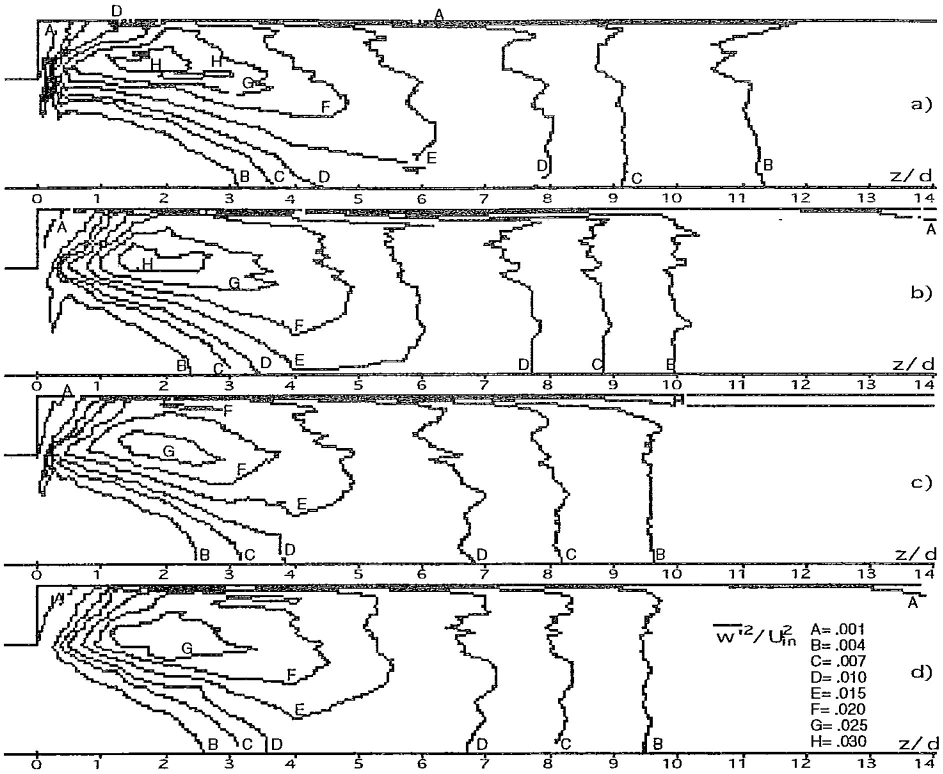

FIGURE 8- NORMALISED TANGENTIAL NORMAL REYNOLDS STRESS. a)WATER Re= 178,000 b) 0.4% TYLOSE Re= 7,950 c) 0.4% TYLOSE Re= 12,150 d) 0.5% TYLOSE Re= 7,600.

bopol solutions reported by Pak et al (1990) and the theories and conclusions developed in this work.

CONCLUSIONS

Mean and turbulent velocity flow characteristics of low molecular weight polymer solutions of low elasticity were measured in an axisymmetric sudden expansion.

The recirculation bubble length of the 0.4% Tylose solutions was seen to be reduced by 10% compared to the water flow for Reynolds numbers above 8,000, and a decrease in the Reynolds number below this value was seen to increase its size again. However, the observed changes in mean flow were not so significant as those reported by Pak et al (1990) in their comparison between inelastic and very elastic fluids.

In spite of the low elasticity of the shear-thinning fluids, reductions of 7, 14 and 30% were observed in the axial, tangential and radial components of the normal Reynolds stresses between the 0.4% Tylose flow at Reynolds number of 12,000 and the water flow at a Reynolds number of 178,000. This dampening of turbulence was seen to be less intense than that reported with more elastic fluids in the flow downstream of a confined baffle of Pinho and Whitelaw (1991).

It was concluded that the large lengthening of the recirculation bubble of very elastic fluids, such as polyacrylamide solutions, reported by Pak et al (1990) must be associated with a very strong dampening of turbulence within the shear layer downstream of the sudden expansion, especially in the transverse directions, as happens in wall flow with the same fluids.

Finally, the important role of elongational viscosity on this phenomena and the non-availability of this rheological measurement in standard commercial equipment means that in future non-Newtonian turbulent flow investigations, the researchers should attempt to characterise the elasticity of the fluids indirectly, for instance via friction factor measurements in a turbulent pipe flow.

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