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The influence of the injection system on drag reduction

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Abstract: The influence of the injection system for centerline injected polymer solutions (threads) on drag reduction in a turbulent pipe flow was studied using injectors of different length and grids. Compared with a short injector, the long injector showed a different behavior: the drag reduction was lower and its onset point was shifted to higher Reynolds numbers.

The velocity profiles for the polymer-phase and the water-phase were measured simultaneously with a combination of laser-Doppler-velocimetry LDV and laser-induced fluorescence LIF. It was found that the analysis of the LDV-measurements with respect to the difference in velocity between the polymer-phase and the water-phase can give information about the mixing between both phases. For a Reynolds number of 30000 the difference between the phases is comparatively large for low drag reduction and very small for high drag reduction. The results indicate that the drag reduction achieved by injecting a concentrated polymer solution is mainly caused by a mixing process between polymer and water.

Key words: Heterogeneous drag reduction – pipe flow – turbulence

Introduction

It was in the early findings of Toms (1948) and Mysels (1949) that a low concentration of polymer in a solution can bring about a turbulent friction resistance much less than that of the pure solvent. This phenomenon was later called homogeneous drag reduction, and the reduction of the friction factor by injecting a concentrated polymer solution from a nozzle into turbulent pipe flow (a "thread") – non-homogeneous or heterogeneous drag reduction.

The first injection experiment in which polymer was injected into the turbulent core of a pipe flow was described by Wells and Spangler (1967). They found that, when the polymer solution was injected into the turbulent core, no reduction in the local pressure gradient occurred until the polymer diffused into the wall region.

Vleggar and Tels (1973) injected a highly concentrated polymer solution in a pipe flow with Reynolds numbers above 25000. They found that the polymer solution formed a thread which preserved its identity even far from the location of the injection point, and the drag reduction was higher than for a homogeneous solution with identical overall polymer concentration.

Since then, non-homogeneous drag reduction was studied by many investigators (Sellin and Moses, 1984; Gyr, 1990). Hoyt and Sellin (1991) found that threads are effective only at low turbulent Reynolds numbers, and at high Reynolds numbers (above 25000) centerline concentrated polymer injection acts as an efficient mixer. Usui (1990) and Berman (1990) investigated the drag reduction caused by a thread at low Reynolds numbers by the measurement of separate velocity profiles for the water-phase and the polymer-phase.

Smith and Tiederman (1991) used a fluorescent dye to study the diffusion of an injected polymer solution in a turbulent pipe flow. Their results indicated that the drag reduction is caused mainly by small amounts of diffused polymer from the thread.

Using a hollow needle to inject a highly concentrated solution of polyacrylamide (Separan AP 45), Bewersdorff (1989) found that the ratio of the injection velocity to the mean velocity has a strong influence on drag reduction measured downstream in the pipe. The ratio of the two velocities was varied by changing the cross-section of the injector.

As a result of the drag reduction studies, it can be summarized that the magnitude of non-homogeneous drag reduction depends on the following parameters:

$$\mathrm{DR} = f(Re, c_p, c_{av}, d, P, I) \quad ,$$

where Re is the Reynolds number, c_p the concentration of the injected polymer, c_{av} the polymer concentration averaged over the cross-section of the pipe, d the diameter of the pipe, P stands for the polymer type, and I designates the injection system. The purpose of the present work was to study the influence of the injection system on non-homogeneous drag reduction.

Experimental set-up

The experimental set-up is described in Fig. 1. A Mohno pump is used to pump water from a storage tank through a surge tank (which is used to damp the fluctuations of the pump) into the main pipe. This pipe was made from acrylic glass and had an inner diameter of 50 mm and a total length of ca. 16 m. The temperature of the water was determined by a resistance thermometer mounted in the entrance section of the pipe, and the rate of flow was measured by an inductive flowmeter positioned between the pump and the surge tank. In order to measure the pressure drop, the pipe was provided with pressure taps in different positions, which could be connected in variable combinations to a differential pressure transducer. The output signal of the pressure transducer, the flowmeter, and the thermometer were fed into a HP 9000/332-Computer by an A/D converter.

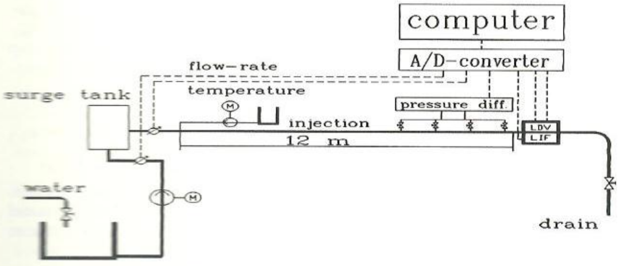

Fig. 1. Experimental set-up

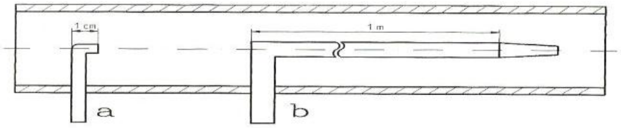

Fig. 2. Injection system: a) short injector, b) long injector

To inject the polymer solutions into the water-flow with a dosing pump, two different injection systems were used. One type of injector consisted of a bent hollow needle whose length in flow direction did not exceed 1 cm (Fig. 2a). The other injection system was made from a pipe of 1 m length and 12 mm outer diameter with the possibility to adjust nozzles of different diameters at its outlet (Fig. 2b). This considerable length was chosen to avoid influences on the injection from the wake of that part of the injector, which is not positioned in line with the flow direction.

Two types of grids were used with the long injector to increase the turbulence at the injection point. The radial grid (Fig. 3) consisted of two rings with 20 bars, which each had a diameter of 1.5 mm and a length of 18 mm; the ratio between the open area of the grid and the total cross-section was 0.7. The second type used was a honeycomb grid of 30 mm length with rectangular channels of 1 mm^2 (Fig. 4); here, the ratio of open to total area was 0.64. The grids were placed 2 cm upsteam from the outlet of the long injector so that the polymer was injected in a location where the grid-generated turbulence reached a maximum.

In some of the experiments the concentrated polymer thread was injected into a homogeneous polymer solution with a concentration of 1 ppm. To prepare the homogeneous polymer solution for these experiments, without the risk of degradation while circulating it through the system, a polymer solution with a concentration of 500 ppm was injected with the short injector in the entrance of the pipe and a honeycomb grid located downstream. Due to strong

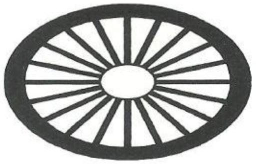

Fig. 3. Radial grid

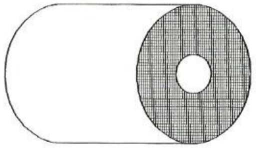

Fig. 4. Honeycomb grid

mixing with the main flow it could be assumed that after 7 m a sufficiently homogeneous solution was achieved[1]. Into this solution the long injector was placed and the concentrated polymer solution could be injected.

To find out how the different injections influenced the profile of the flow a laser-Doppler-velocimeter (LDV) was installed at the end of the main pipe. The LDV worked with an Ar-ion laser in back-scattering mode with a frequency tracker as signal processing device. Since the polymer thread represents a second phase in the flow a combination of LDV and laser-induced fluorescence (LIF) was used to measure separate velocity profiles for the water-phase and the polymer-phase simultaneously. To separate the velocity data of the LDV it was necessary to decide which of the phases has been in the measuring volume of the LDV.

The optical set-up of the combination of LDV and LIF is shown in Fig. 5. The polymer was dyed with fluorescein, which emitted fluorescent light of high intensity when the polymer thread passed the laser beam of the LDV. Since only the fluorescence in the intersection of the laser beams is relevant, the fluorescence-detector had to be adjusted exactly on the intersection. Therefore, the plane in which the beams intersect is focused on the detector with a lens system. The first lens magnifies the intersection which allows to cut off light coming from the laser beams not intersecting with a diaphragm. The remaining picture is focused on the detector with a second converging lens. An orange filter is used to cut off laser light scattered from the tracer particles in the flow. The traversing and focusing of the detection system is done manually by replacing the detector with a ground glass. The detector itself is a simple photodetector with an amplifier converting the signal to a voltage between 0 and 10 Volts.

The decision about whether a velocity signal has been taken for the water-phase or the polymer-phase, is based on the fluorescence signal which was taken almost simultaneously[2] with the velocity signals. Therefore, from the mean fluorescence intensity two thresholds were calculated that represent the maximum intensity for detection of the water-phase and the minimum intensity for the polymer-phase. With these thresholds a separation of the mean velocity profile into two separate profiles was possible.

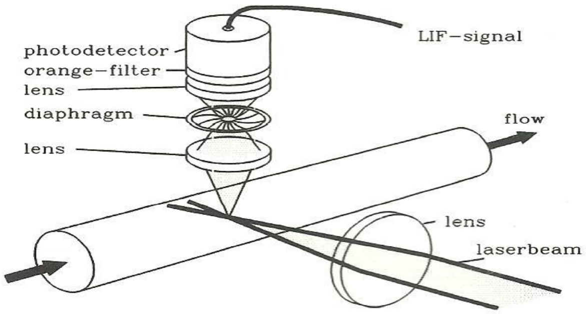

Fig. 5. LDV/LIF-set-up

Since the injection system with the long injector formed a separate unit, it could be placed in different positions of the pipe. In this way it was possible to measure velocity profiles and local pressure drops in different distances from the injector. The maximum distance between the injection system and the LDV-section used in this investigation was 12 m.

The polymers used were the anionic polyacrylamides Separan AP 273, which was used for the study of the influence of different injectors on the friction factor, and Separan AP 45, which was used in all the other experiments (both manufactured by Dow Chemicals Inc.). The concentrated polymer solutions, which usually had a concentration of $c_p = 4000$ weight ppm, were prepared by suspending the polymer together with some aluminum tracer particles necessary for LDV and a small amount of fluorescein in isopropanol. This mixture was then added to the desired amount of deionized water and stirred gently for about 48 h.

Results

The measured local pressure drop in the pipe can be used to calculate the wall shear stress τ_w and the friction factor f as

$$\tau_w = \frac{\Delta p \cdot d}{4 \cdot L} \ , \quad f = \frac{8 \cdot \tau_w}{\varrho \cdot U^2} \ , \tag{1}$$

where $\Delta p/L$ denotes the pressure drop per unit length, d the diameter of the pipe, ϱ the density, and U the bulk velocity of the fluid. The drag reduction

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[1] It was found that after 7 m the drag reduction did not depend on the distance from the injector.

[2] The sample rate of the A/D converter was 30 kHz.

DR is calculated by comparing the friction factor of the drag reduced flow f_p with that of the pure solvent f_s:

$$\mathrm{DR} = 1 - \frac{f_p}{f_s} \; . \tag{2}$$

The velocity profiles were normalized with the wall shear velocity u_τ:

$$u_\tau = \sqrt{\frac{\tau_w}{\varrho}} \, , \quad u^+ = \frac{u}{u_\tau} \, , \quad y^+ = \frac{y \cdot u_\tau}{\nu} \, , \tag{3}$$

where u^+ and u stand for the velocity, y^+ and y for the distance from the wall, and ν for the kinematic viscosity of the fluid. Since it was impossible to measure the pressure drop across the LDV/LIF-measuring section, and the drag reduction depended on the distance from the injection point, the wall shear stress, used to normalize the profiles, had to be calculated from separate pressure drop measurements.

The first thing to investigate was the influence of the injection system on heterogeneous drag reduction. In this case the length of the injector and its diameter were chosen as the most important factors. Therefore, in the first series of experiments two different injectors having the same diameter $d_{\mathrm{inj.}}$ and different length (see Fig. 2) were used to inject a 4000 ppm-solution of the anionic polyacrylamide Separan AP 273. Figure 6 shows the results of friction factor measurements for Reynolds numbers between 10000 and 50000, where the short injector clearly shows much higher drag reduction than the long one: e.g., at a Reynolds number of 30000 the drag reduction reached 48% for the short injector and 10% for the other one 12 m downstream from the injection point. The data indicate that the drag reduction at high Reynolds numbers, above ca. 20000, using the long injector, is mainly due to mixing effects in the pipe flow, as reported with different injectors by other investigators (Hoyt and Sellin, 1991), and the increase in drag reduction using the short injector should be due to more intensive mixing. On the other hand, for the long injector there is no detectable drag reduction at Reynolds numbers less than 20000.

For the purpose of examining the influence of the injection velocity on drag reduction and its development with the distance L between the injector and the measurement point of the pressure drop, using the long injector, different diameters of nozzles were used in the injection experiments at a Reynolds number of 30000. The use of different diameters of the nozzles results in a change of relative injection velocity u^*, which is defined as the ratio between injection velocity and mean flow velocity. The concentration of the injected polymer solution c_p was 4000 ppm and the average concentration c_{av} was 6 ppm. Figure 7 shows the drag reduction caused by using two different nozzles. The comparison between the two experiments demonstrates that there is no clear difference in drag reduction due to the diameter of the injector.

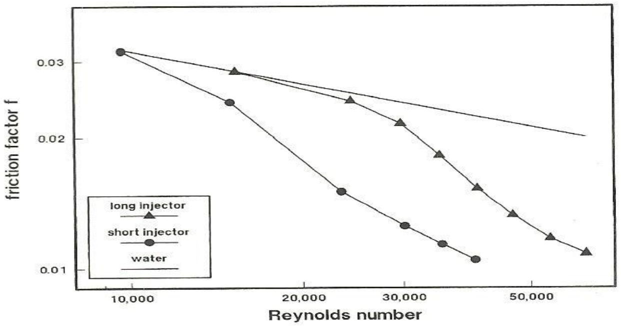

Fig. 6. Influence of injectors on the friction factor; Separan AP 273, $c_p = 4000$ ppm, $c_{av} = 12$ ppm, $d_{inj.} = 4$ mm

Figure 7 also shows the results of the next series of experiments, where two different types of grids were used. Here, the honeycomb grid produces a drastic increase of drag reduction and the level of drag reduction is not significantly influenced by the different diameters. The other grid shows a different behavior where the diameter of the nozzle is of influence. However, even with the small nozzle the level of drag reduction achieved with the honeycomb grid is never reached. The slope of the development of the drag reduction with the distance shows only comparatively small differences for the different experiments.

To study the development of the mixing process with the distance using the long injection system, the first series of LDV-measurements was made without a grid at different distances from the injector. Figure 8 shows a velocity profile for Newtonian water flow and the profiles for the two phases of an injection experiment, where the distance from the injector was 2 m and the polymer was injected with the nozzle of diameter 2 mm. Since at this distance there is no visible drag reduction, the profiles for water and the water-phase, which represents the main phase, are almost equal. It should be noted that the small dif-

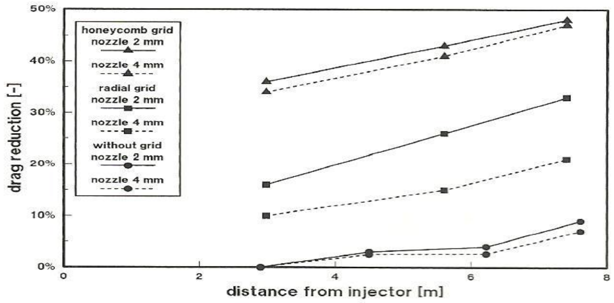

Fig. 7. Influence of grids and distance on drag reduction; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $Re = 30000$

ference between the pure water and the water-phase is due to the normalization of the profiles, which was made for all the LDV-measurements.

The measurements in Fig. 8 show a big difference between water- and polymer-phase in the core region of the flow. Comparing this profile with the profiles of Figs. 9 and 10 which were measured under the same conditions at distances of 4.6 m and 8.55 m, respectively, it is found that due to higher drag reduction the profiles are shifted to higher values of u^+. It can also be seen that the difference between the two phases is decreasing with increasing distance, i.e., increasing drag reduction. The measurements were repeated under the same conditions but with a nozzle of diameter 4 mm, which reduced the relative injection velocity u^* from 100% ($d_{\text{inj.}} = 2$ mm) to 25%. As in the drag reduction measurements, here, also no significant difference was found between the two profiles.

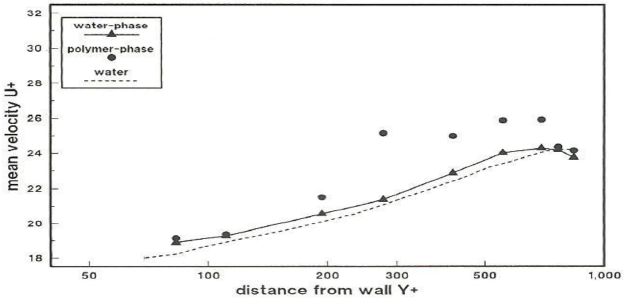

Fig. 8. Velocity profiles; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $d_{\text{inj.}} = 2$ mm, $L = 2$ m, DR = 0%, $Re = 30000$

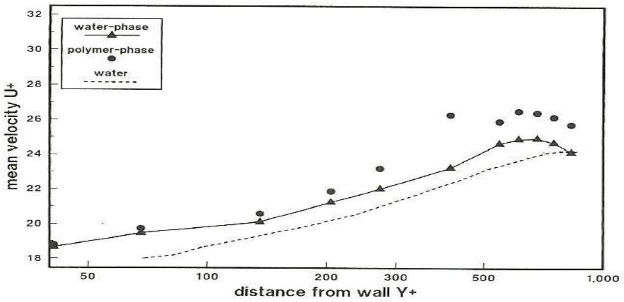

Fig. 9. Velocity profiles; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $d_{\text{inj.}} = 2$ mm, $L = 4.6$ m, DR = 3%, $Re = 30000$

In order to get an idea of the influence of the different grids on the mixing rate of the injected polymer at high Reynolds numbers, the second series of LDV-measurements was made under the same conditions with a nozzle of diameter 4 mm. Figures 11 and 12 show the velocity profiles measured using the radial and the honeycomb grid. It can be seen in these figures that the difference between the two phases is larger for the radial grid than for the honeycomb grid which shows a much higher drag reduction (see Fig. 7).

In Fig. 7 an effect due to the diameter of the nozzle appears clearly only for the radial grid. Here, it is interesting to note that the drag reduction in this case was lower for the lower ratio of injection velocity, which stands in contrast to the results of Bewersdorff (1989) who used a short injection system.

To find an explanation for this result, a velocity profile was measured with a nozzle of diameter 2 mm,

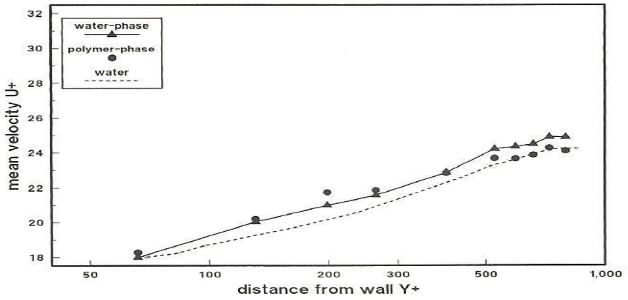

Fig. 10. Velocity profiles; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $d_{\text{inj.}} = 2$ mm, $L = 8.55$ m, DR = 8.5%, $Re = 30000$

using the radial grid (Fig. 13). The comparison between the profiles in Figs. 11 and 13 demonstrates that the rate of mixing for 2 mm is higher than for 4 mm, which can explain the increase in drag reduction.

The influence of mixing can be also studied in Fig. 14, where different amounts of a polymer solution with a concentration of 4000 ppm are injected into a water flow. Obviously, the drag reduction, which was measured at a distance of 7.6 m downstream from the injector, decreases with increasing amount of injected polymer and reaches a constant level for concentrations higher than 15 ppm. The reason for this effect is the stability of the polymer thread, whose diameter and resistance to fragmentation is increasing with increasing average polymer-concentration. Therefrom, it can be concluded that the drag reduction for low polymer-concentrations is due to the dissolution of small amounts of the polymer in the mean flow.

To limit the influence of polymer dissolved from the injected polymer, a concentrated polymer solution was injected into a homogeneous polymer solution with a concentration of 1 ppm. The result is shown in Fig. 14, where the dashed line represents the drag reduction for the homogeneous solution. The additional injection of a concentrated polymer thread leads to no further increase in drag reduction.

The measurement of the velocity profiles at a distance of 8.55 m downstream from the injector for the injection of a concentrated polymer thread in a homogeneous solution is shown in Fig. 15. Since a large difference in the mean velocities between the two phases was found to be an indicator of a low intensity of mixing, it can be understood that the injected polymer solution does not cause an increase in drag reduction.

Discussion

The experimental results demonstrate that the length of the injector has a substantial influence on drag reduction. Compared to a short injector with the same injection velocity, the long injector shows lower drag reduction, an onset point shifted to higher Reynolds numbers, and no significant influence of the diameter of the injector. This observation can be explained from the high level of turbulence in the wake of a short injector due to the close proximity of the transverse tube element of the injector.

It is interesting here to note that Bewersdorff (1989) found a strong influence of the short injector's

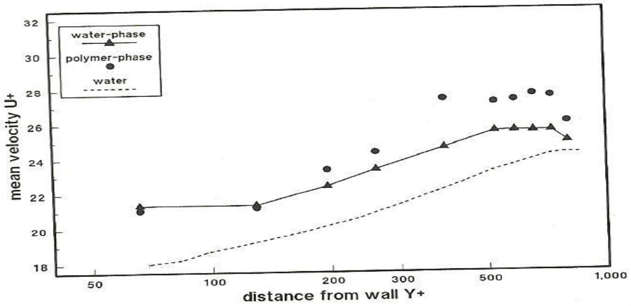

Fig. 11. Velocity profiles with radial grid; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $d_{\text{inj.}} = 4$ mm, $L = 4.6$ m, DR = 13%, $Re = 30000$

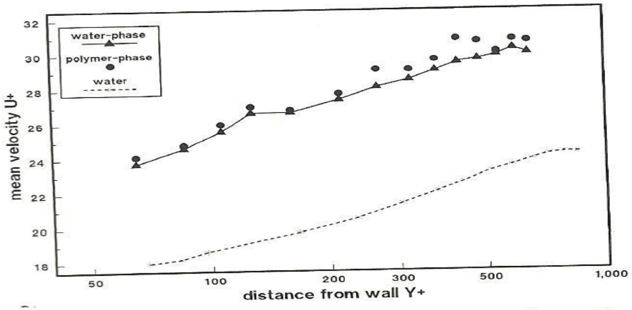

Fig. 12. Velocity profiles with honeycomb grid; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $d_{\text{inj.}} = 4$ mm, $L = 4.6$ m, DR = 38%, $Re = 30000$

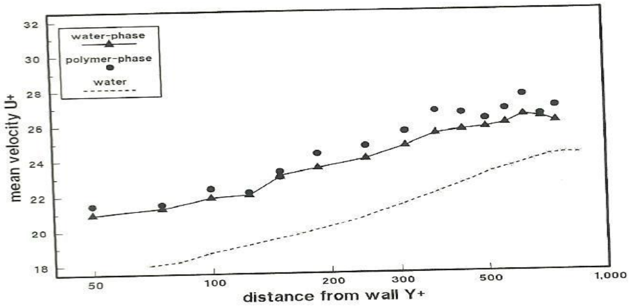

Fig. 13. Velocity profiles with radial grid; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $d_{\text{inj.}} = 2$ mm, $L = 4.6$ m, DR = 22%, $Re = 30000$

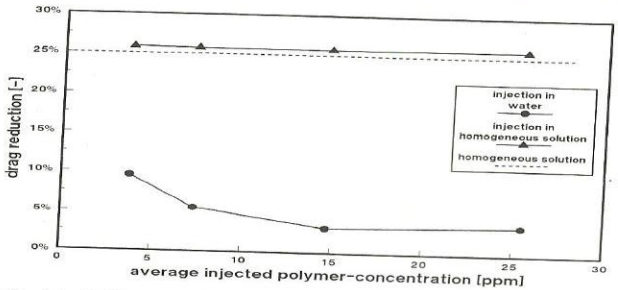

Fig. 14. Influence of average injected polymer-concentration on drag reduction; $c_p = 4000$ ppm, $c_h = 1$ ppm, $d_{\text{inj.}} = 4$ mm, $L = 7.6$ m, $Re = 30000$

diameter on drag reduction. Since this effect was not found with the long injector, it can be assumed that the change of diameter of a short injector does not only change the injection velocity, but also the flow conditions in the wake of the injector.

As the flow conditions at the outlet of the injector seem to be very important for the drag reduction, different grids were used to increase the turbulence intensity behind the long injector. When the polymer was injected with a honeycomb grid, the polymer-phase did not form a continuous thread, but was disrupted into fragments. The high level of drag reduction, obtained in this case, originates from the high rate of mixing, and the velocity profile also shows a very small difference between polymer-phase and water-phase (Fig. 12).

The analysis of the LDV-measurements with respect to the difference in velocity between the polymer-phase and the water-phase can give information about the mixing between both phases. In Figs. 8 and 15, where only very small drag reduction occurs, the difference is comparatively large, while in Fig. 12, where high drag reduction was observed, the difference becomes very small. These results indicate that the main reason for drag reduction caused by injecting a concentrated polymer thread in a highly turbulent flow is mixing, which agrees well with the results of Hoyt and Sellin (1991).

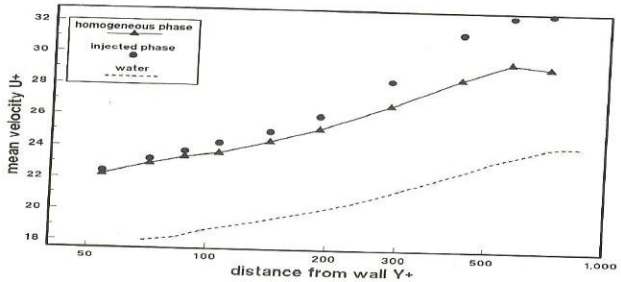

Fig. 15. Velocity profiles of injected polymer into homogeneous solution; $c_p = 4000$ ppm, $c_{av} = 6$ ppm, $c_h = 1$ ppm, $d_{\text{inj.}} = 4$ mm, $L = 8.55$ m, $Re = 30000$

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