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Smoother than smooth: increasing the flow conveyance of an open-channel flow by using drag reduction methods

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Abstract

The drag reduction method by polymer additives is a common strategy used to minimize friction losses when carrying fluids (water, oil, slurries) in pipes over long distances. Previous studies showed that the interactions between the polymer and the turbulent structures of the flow tend to modify the streamwise velocity profile close to the walls by adding a so-called elastic sublayer between the classical viscous and log layers. The gain in linear head losses can reach up to 80%, depending on the roughness of the walls and the concentration of polymers. The application of this technique to sewers and the subsequent gain in discharge capacity motivated this work to quantitatively measure the drag reduction in classical open-channel flows. Three measurement campaigns were performed in a dedicated long flume for several water discharges and several polymer concentrations: backwater curves over smooth and rough channel walls (including velocity and turbulent shear stress profiles) and flows around emerging obstacles. The addition of polymers, even in limited concentrations, allowed a high friction decrease with a typical Darcy-Weisbach coefficient reduced by factors of 2 and 1.5, respectively in smooth and rough walls configurations without obstacles; but without strong modifications of the non-dimensional velocity profiles. Oppositely, when adding emerging obstacles,

the flow was unaffected by the inclusion of polymers, in agreement with the prediction of the literature. The drag-reduction method by addition of small concentrations of polymers finally appears to be a promising technics to increase the flow conveyance in open-channel flows.

Introduction

Discovered by Toms in 1948 (see Toms, 1949), the drag reduction effect by polymer addition is a common strategy used to minimize friction losses when carrying fluids over long distances. This effect is commonly used "in oil pipeline conduits, oil well operations, flood water disposal, firefighting, field irrigation, transport of suspensions and slurries, sewer systems, water heating and cooling systems, airplane tank filling, marine systems, and biomedical systems including blood flow" (Brostow, 2008). Han et al (2017) recently reviewed all available water-soluble macromolecules that permit to reduce the drag of turbulent flows, "including both natural and synthetic polymers". While drag reduction can also be obtained by inserting other additives in water, such as fibers or surfactants, this paper only deals with polymeric additives. Moreover, the present work is limited to solutions with very low polymer concentrations (a few tens of parts per million *ppm*).

The drag reduction effect allows to dramatically reduce the wall friction and thus the linear head losses by up to 80% (Herzhaft, 2000; White et al., 2018). The origin of this phenomenon lies in the interactions between the turbulent structures of the flow and the polymer macromolecules added to the fluid (Schlichting, 1979). In a fully-developed flow over a smooth bed, the polymers modify the velocity profile in the boundary layer. With clear-water, the velocity profile in the near-wall regions is composed of the laminar viscous sub-layer very close to the wall ($yu_*/\nu<10$ with y the distance to the wall, u^* the friction velocity and ν the kinematic viscosity of the liquid) and the log law slightly further away ($yu_*/\nu>50$). When adding polymers, a so-called "elastic zone" can be observed in between these two zones, for $y^+>15$ (Virk, 1975, Cai et al., 2009), within which the velocity profile follows a logarithmic law with a slope that depends on the polymer concentration. It is reported that as the extension of this zone increases, the drag reduction efficiency also increases. If this elastic zone occupies the whole flow section, the maximum drag reduction asymptote (*MDRA*) is reached and

increasing the polymers concentration will not permit to further reduce the friction coefficient. However, White et al. (2018) recently suggested that when approaching the MDRA, the velocity profile tends to depart from a logarithmic law. They also observed that as the drag reduction increases, the extension (away from the wall) of the viscous sublayer increases and in return, the logarithmic or quasi-logarithmic layers are moved further away from the wall. Moreover, Virk (1975) shows that drag reduction can only be observed for a minimum wall shear stress magnitude.

Virk (1971) also investigated the possibility of polymers to reduce the drag over rough surfaces. He observed that for walls with large enough roughness elements, the wall roughness tends to decrease the drag reduction process. The author could establish useful asymptotic regimes of drag reduction as a function of the relative roughness, flow and polymeric parameters. These regimes are based on the common non-dimensional roughness height parameter k_s^+ defined as $k_s^+=k_s u_*/\nu$, with k_s the equivalent sand roughness height. His main conclusions are that, for a water-polymer mixture, the effect of wall roughness begins to be effective for $k_s^+>12$ (compared to $k_s^+>5$ in pure water). This confirms that the extension of the viscous sublayer increases when adding polymers. Then for $12<k_s^+<50$, an "effectively smooth regime" is observed, and for $k_s^+>50$ the drag reduction decreases compared to the smooth regime up to the experimental limit of $k_s^+\sim150$.

On a local scale, the interactions between the polymer and the turbulent structures (of different scales) remain poorly understood and research on this topic is still going on (Herzhaft, 2000). Achia and Thompson (1977) and Tiederman et al. (1985) showed that the polymers tend to decrease the frequency of occurrence of the so-called turbulent ejections ($w'>0$ et $u'<0$ with w the wall normal and u the streamwise velocity components and where the prime denotes time-fluctuations) and to increase their transverse spacing. The streamwise turbulent Reynolds stress increases while the wall-normal component decreases (see Harder and Tiederman, 1991). Moreover, the Reynolds shear stress in the elastic zone decreases due to the polymer insertion so that the total stress also decreases. A hypothesis is that aggregates of polymers of size comparable to the smaller turbulent scales can limit the existence of these small scale turbulent structures and thus limit the global turbulent intensity. Min et al (2003) proposed the following mechanism: the polymers in the very near-wall region store elastic energy

taken from the flow and release it further from the wall as they are transported to the buffer layer by coherent turbulent structures.

Most works, cited above, report the use of drag reduction polymers in pressurized pipe or channel flows. However, a few tests have also been performed in open-channel flows, especially within sewer systems (see Sellin 1988). Hart et al (2011) reported the use of such polymers in the sewer network of the city of Whistler (Canada) during the 2010 Winter Olympic games where the waste water discharge was strongly increased due to a particularly high population in the area. Their figures 6-7, for instance, show a strong water depth decrease and velocity increase in a given open-channel pipe flow during a "high flow polymer dosing trial": in about one hour, the typical water depth decreases from about 15 to 2cm while the typical velocity increases from 2.2 to 3.4m/s. Use of polymers in urban flows is made possible by the Materials Safety Data Sheet (MSDS) information for anionic polymers that indicates that the chemicals are non-toxic at limited dose concentrations (Hart et al. 2011). Apart from these engineering applications in sewer networks, very little attention seems to have been devoted to drag reduction in open-channel flows. Janosi et al. (2004) investigated the effect of adding polymers to a dam break flow experiment on both initially dry and wet beds. Their results confirm Cadot et al (1998) observations that drag reduction is only effective if "turbulence is forced by a smooth boundary layer and the phenomenon vanishes in inertially forced turbulent flows".

To conclude, even though drag reduction is commonly used in pressurized flows, no academic work could be encountered on the analysis of drag reduction additives in open-channel flows (representatives of river or sewer flows). The aim of the present work is thus to fill this gap and estimate the drag reduction efficiency in open-channel flows over smooth and rough beds, with and without obstacles. The dedicated experimental open-channel flume and measurement techniques are introduced in section 1 along with a description of the tested polymer additives. Then, the flow characteristics (water depths and velocity profiles) are measured with and without polymers and compared to each other i) under smooth bed conditions in section 2, ii) under rough bed conditions in section 3, and iii) under smooth bed conditions but with a series of emerging obstacles in section 4.

Experimental set-up

Polymers are tested herein in open-channel configurations using natural ground water at temperatures between 10°C and 20°C, with and without polymers. The additives are water-soluble polyacrylamide polymers (PAM or PAAM), commonly used as flocculants in water treatment processes (drinking water and waste water), as described by Han et al. (2017). Fig. 1 shows the results of rheological tests performed with the natural water without and with polymers collected at the inlet and outlet of the flume. It reveals that the water/polymers mixture remains Newtonian and its viscosity increases by about 15% compared to plain water and also reveals that the flow in the flume tends to decrease this viscosity increment due to shearing effect on the polymers.

Figure 1

The experiments presented below took place in the laboratory of SNF at Andrezieux in France. A specific flume was designed and installed to investigate the effect of drag reduction additives on open-channel flows in different conditions. The 435m long flume is smooth, made of fiberglass and epoxy resin with a typical roughness size of 1.6 μm, of b=12cm wide rectangular cross-section with a constant streamwise slope S_0=0.011% (see Fig. 2). Note that only the 100m downstream-most reach is used for measurements. Underground natural water is pumped before the experiments and stored in a large tank. The inlet then permits to release this water directly towards the flume or to mix it with a controlled concentration of polymers aqueous solution before reaching the flume. The inlet discharge Q is controlled and measured in the upstream feeding system using valves and an electromagnetic flow meter. At the downstream outlet, the flume ends with a free-fall, imposing a critical flow condition before the water is evacuated outside the laboratory.

Figure 2

Water depths h are measured using an ultrasonic radar sensor probe (Vegapuls 64 from VEGA) from above the flume. The displacement of the ultrasonic probe along the streamwise axis x of the flume then permits to measure backwater curves. The 3 components of the flow velocity are measured at high sampling frequency locally using an acoustic Doppler velocimeter (16MHz ADV from Sontek).

To improve the signal backscattering, tracers are added to the water and it was verified that these tracers do not affect the impact of the polymers on the drag reduction. The vertical displacement of the velocimeter finally permits to measure vertical profiles of velocity.

Smooth bed experiments

Backwater curves and friction coefficients

This section aims at characterizing the drag reduction due to additives diluted in the water in an open-channel flow with smooth walls. To do so, five different upstream discharges (see Table 1) are set, under steady state conditions without or with different controlled concentrations of polymers. Keeping a critical downstream depth, a total of 21 subcritical backwater curves are finally measured. Figure 3 exhibits the measured backwater curves over the downstream 100-meters channel reach for a selected discharge without and with four polymer concentrations. Similar figures for other discharges (not shown here) exhibit similar behaviors. Fig. 3 confirms that i) the use of polymers decreases the water depths and, in return increases the flow velocity over the whole measured reach, ii) the water depth reduction increases with the increasing polymer concentration and iii) that the drag reduction does not increase anymore as the polymer concentration exceeds 20 to 30 ppm, in agreement with the concept of maximum drag reduction asymptote (MDRA, see White et al., 2018).

Fitting the backwater curve measured with plain water based on the Colebrook-White equation permits to estimate the equivalent bed roughness of the flume to $k_s \sim 10^{-4}$m. Nonetheless, when using a water/polymer mixture, the Colebrook-White equation does not apply anymore. Consequently, the measured curves are rather fitted using a constant averaged Darcy-Weisbach friction loss coefficient λ using:

$$\frac{dh}{dx} = -\frac{8g\left(bh\right)^3 S_0 - Q^2\lambda\left(b+2h\right)}{8b\left(b^2h^3g - Q^2\right)} \quad (1)$$

155 with g the acceleration of gravity. Fig.3 confirms that such simplification still fits the measured
156 backwater curves with high fidelity both with plain water (leading to $\lambda \sim 0.017$, in agreement with
157 Moody diagram) and with water/polymer mixtures (leading to lower Darcy-Weisbach coefficients).

158 *Figure 3*

159 The best-fit Darcy-Weisbach coefficients for the 5 tested discharges with plain water and a polymer
160 concentration of 20 ppm are summarized in Table 1. For a given discharge, the difference in water
161 depth with / without polymers leads to a very limited difference in Reynolds number but to a strong
162 decrease of friction coefficient: λ is reduced by a factor of about 2 for all discharges. Similarly, the
163 water depth is reduced (and correspondingly the average velocity is increased) by a factor of about 1.1
164 to 1.2, i.e. 10% to 20%. When plotting these results on the well-known Moody diagram (giving λ as a
165 function of the Reynolds number and relative roughness for water), the resulting Darcy-Weisbach
166 friction factor λ appears to be much lower than what can be obtained by the hydraulically-smooth
167 curve (not shown here). To conclude, the drag reduction in open-channel flows by adding polymers
168 exceeds that of using a perfectly smooth wall, in agreement with pipe flow measurements, reported
169 among others by Tanner (1988).

170 *Table 1*

171 *Velocity profiles*

172 The present section aims at comparing the vertical profiles of velocity and Reynolds shear stress
173 measured in the smooth open-channel flow with and without the additives. Velocity profiles are
174 measured over the lower 70% of the flow section using the ADV at a fixed streamwise location
175 (x=6.87m) for two discharges (Q=50 and 100 m^3/h) without polymers and with a concentration equal
176 to 20 ppm. Fig. 4 compares the velocity profiles made non-dimensional using the water depth h and
177 average velocity U_b.
178 It appears that the four velocity profiles are quite similar to each other and exhibit the expected global
179 shape: a log region near the bed and a quite constant velocity profile further up in the water column in

the bulk. In Fig. 4, b/h ranges from 0.7 to 1.3 (with b the channel width and h the local water depth) and these profiles are indeed highly similar to typical velocity profiles of narrow and deep open-channel flows in the literature, as shown, for instance by Rendu et al. (2017) with b/h~1.1 or Bonakdari et al. (2008) with b/h~1.8. Unfortunately, the ADV is not able to measure the details of the velocity profiles in the near-bed region to highlight the transitions between viscous, elastic (with additives) and logarithmic sub-layers. such measurements would require techniques such as PIV (as for Cai et al., 2009) which could not be implemented in the present flume as the lateral walls are not transparent.

Fig. 4 also plots vertical profiles of Reynolds shear stress for the same conditions. The four profiles are in qualitative agreement with a limited shear stress in the upper part of the water column (z/h>0.2) and a rapid increase when approaching the bed, with a maximum shear stress measured at z/h~0.1. These profiles are also in qualitative agreement with measurements without polymers by Kironoto and Graf (1995) and the recent calculations without and with polymers performed by White *et al.* (2018), see their figure 6.

Figure 4

Rough bed experiments

The previous section showed that the additives permit to reduce the resisting wall friction in smooth bed conditions. The aim of this section is then to verify whether this drag reduction is still observed with a rough bed. The downstream-most, 24 meters long, reach of the flume is modified by including rough walls made of aluminium tear plates of typical tear roughness height equal to 1 mm (see Fig. 2). The resulting channel width then reduces to b_2=11cm.

Similar backwater curves as for the smooth case are measured and plotted in Fig.5 with a critical depth downstream, for two discharges without additives and with 20 ppm of polymers. As for the smooth bed configuration, the water depths appear to strongly decrease when the polymer is included. When using plain water, the best-fit equivalent roughness height increases to k_s~4mm, which corresponds to an average Darcy-Weisbach coefficient equal to λ~0.05 for both discharges (Fig. 5). This result is in

agreement with that of the Moody diagram: for Q=100m^3/h and h~0.35m (see Fig. 5), k_s/D_h=0.021 with D_h the hydraulic diameter and Re=1.4x10^5, the Moody diagram also predicts λ=0.05. When adding 20ppm of polymers, the Darcy-Weisbach coefficient reduces to λ~0.037 for Q=100m^3/h and λ~0.03 for Q=50m^3/h. We thus face a decrease of Darcy-Weisbach coefficient by a factor 1.35 to 1.66 compared to the configuration with plain water, i.e. a smaller decrease than when using a smooth bed but still a notable drag reduction.

Figure 5

Vertical profiles of streamwise velocity are measured in the rough bed configuration in a similar way as for the smooth bed configuration at the same location (x=6.87m) for both tested discharges without and with additives and are shown in Fig.6 in the same way as for Fig.4. As for the smooth bed condition, very similar streamwise velocity profiles are measured without and with additives over the rough bed for both discharges with a quite constant streamwise velocity U_x/U_b~1.2 for z/h>0.4 and a velocity decrease closer to the bed (Kirkgoz, 1989). Regarding the Reynolds shear stress, the maximum shear stresses ($-\langle u_x' u_z' \rangle_{max}/U_b^2$~15x10^{-4}) observed at z/h~0.1 appear to exceed that measured over the smooth bed (Fig.4) but with no notable difference without and with additives.

Figure 6

As proposed by Virk (1971), it is expected that the roughness effect on the flow depends on the ratio between the equivalent roughness height and the width of the viscous and elastic sublayers away from the wall. This ratio is evaluated by estimating the roughness height parameter $k_s^+=k_s u_*/\nu$, where the friction velocity u_* is obtained using $u_* = U\sqrt{\frac{\lambda}{8}}$, with U the average velocity and ν the kinematic viscosity of the water. For a discharge of Q=50m^3/h of the water + 20ppm mixture: U~0.4m/s, u_*~0.024m/s and k_s^+~100 and for Q=100m^3/h: U~0.5m/s, u_*~0.034m/s and k_s^+~135. Both backwater curves measured in the rough bed with a concentration of 20 ppm of polymers (Fig.5) are thus in the so-called completely rough regime (k_s^+>70), according to Nezu and Nakagawa (1993) among others. According to these authors, in a typical water flow in completely rough regime, “viscous effects disappear because the roughness elements penetrate the fully turbulent logarithmic layer”. Besides, for

232 a water + polymer mixture, Virk (1971) shows that drag reduction effects decrease as the equivalent
233 roughness height parameter k_s^+ increases from 12 up to values larger than the experimental limitations
234 of this author: k_s^+~150. The present observation of drag reduction limitation for the present k_s^+=100
235 and 135 is thus in fair agreement with this author's observations in rough pipes.

236 Experiments with emerging obstacles (and smooth wall)

237 The previous section showed the ability of additives to reduce the friction coefficient in flows where
238 the resistance is governed by wall friction. The aim of the present section is to evaluate the effect of
239 additives in a flow which resistance is rather governed by drag forces induced by obstacles (Stone and
240 Shen, 2002), with a negligible contribution to the wall friction. To do so, vertical impervious and
241 smooth obstacles of D=15 mm wide square section are introduced in the flume, deposited on the bed
242 and emerging through the free-surface (Fig. 7). One obstacle is introduced every meter over the 42
243 meters downstream most channel reach. The obstacles are not aligned in the streamwise direction, they
244 are rather randomly located from the left to the right bank. Backwater curves for the Q=100m^3/h
245 configuration are shown on Fig.8 with and without additives (and also without obstacles), in the same
246 way as for Fig.2. This figure first confirms that, when using water, adding the obstacles strongly
247 increases the water depth and thus strongly increases the flow resistance, confirming that the flow
248 resistance is dominated by the drag forces on the obstacles. Moreover, Fig.8 reveals that, in such case,
249 the additives do not permit to reduce the flow resistance and lead to a very similar backwater curve as
250 when using plain water.

251 *Figure 7*

252 This incapacity of polymers to decrease the drag forces induced by the obstacles is in agreement with
253 the recent findings of Xiong *et al.* (2017) on the drag reduction effect in flows interacting with an
254 isolated obstacle. To do so, the authors introduce a Reynolds / Weissenberg number phase diagram
255 upon which they indicate the regions for which the drag force induced by the obstacle is reduced,
256 unaffected and enhanced by the inclusion of polymers in the fluid. In the present case, the Reynolds
257 number based on the obstacle diameter equals:

$$Re_D = UD/\nu \sim 0.6x0.015/10^{-6} \sim 8000 \quad (2)$$

and the Weissenberg number (viscous to elastic forces ratio):

$$Wi = 2U\tau/D \sim 2x0.6x6.7x10^{-3}/0.015 \sim 0.5 \quad (3)$$

with τ the polymer relaxation time estimated as (see Xiong *et al*., 2017):

$$\tau \sim \rho\nu R_o^3/(k_B T) \sim 1000x10^{-6}x3x10^{-7}/(1.38x10^{-23}x293) \sim 6.7x10^{-3}s \quad (4)$$

ρ the density of water (1000 kg/m^3), R_o~3x10^{-7}m the typical size of the polymer statistical sphere, k_B=1.38x10^{-23}J/K the Boltzmann constant and T~293K the fluid temperature. According to figure 4 or 6 from Xiong *et al*. (2017), for Re_D~8000 and Wi~0.5 the obstacle drag coefficient is unaffected by the addition of polymers, which explains why the backwater curves in Fig.8 are so similar with and without polymers.

Figure 8

To conclude, the flow resistance is here governed by drag forces due to obstacles – rather than friction on smooth walls. Considering the associated particulate Reynolds numbers, these drag forces are mainly due to pressure drag and adding polymers has no effect on the head losses and thus on the water depth and average velocity of the flow.

Discussions and conclusions

To the author's knowledge, the present paper is the first work dedicated to the study of the impact of adding to the water a limited concentration of polymers for classical free-surface open-channel flows: 1D subcritical flows over smooth and rough beds, without and with emerging obstacles. These flow configurations are small-scale and simplified versions of typical channel and river flows. These measurements reveal that adding polymers to the water under these conditions:

1) Strongly decreases the drag force that the walls apply on the flow, leading to highly increased mean velocities and highly decreased water depths. The averaged equivalent Darcy-Weisbach

coefficient is decreased by a factor of about 2 for the smooth bed configuration and about 1.5 for the rough bed configuration. The drag reduction is thus still effective but reduced in magnitude with a roughness parameter k_s+ larger than 100, in agreement with previous observations in rough pipes (Virk, 1971)

2) Has no effect on the resistance forces when relatively large obstacles are included in the channel. When the flow resistance is dominated by the drag forces due to these obstacles, the influence of the boundary layers adjacent to the channel walls becomes negligible and no drag reduction is observed anymore, in agreement with Cadot *et al.* (1998) observations.
3) Hardly modifies the vertical profiles of streamwise velocities and Reynolds shear stress at least away from the wall region.

To summarize, at the laboratory scale, as long as the boundary layer developing along the bottom and side walls of the channel governs the resistance forces, the modification of these boundary layers by the additives permits to highly increase the capacity of a watercourse, i.e. to limit the water depths and specifically the overflows over the side banks. Oppositely if the flow resistance is governed by the drag forces on large scale obstacles, the additives have no effect on the watercourse capacity.

This drag reduction method already proved to be effective for reducing the water depth in sewer networks (Sellin, 1988; Hart et al., 2011) and the present work corroborates these observations as the flow resistance in sewers is mainly dominated by wall frictions and the size of the wall roughness remains usually limited. Oppositely, to the author's knowledge, this method was never tested in geophysical flows such as rivers and the following paragraphs discuss first its expected hydraulic efficiency and second its potential environmental issues.

Regarding the hydraulic efficiency of the method in rivers, an estimate of k_s+ for a river reach is given by:

$$k_s+ = \frac{k_s u*}{\nu} \approx \frac{k_s \sqrt{g R_h S_0}}{\nu} \quad (5)$$

where k_s is the equivalent bed roughness and R_h the hydraulic radius. Let us consider k_s+=135 as the threshold for an effective friction reduction by the additives (Fig.5). For typical plain rivers (say $S_0=10^{-4}$), friction reduction is then expected to be effective (Pich, 2014): for small rivers (R_h=1m) if k_s<4.3mm, corresponding to small gravel beds, and for big rivers (R_h=10m) with k_s<1.4mm, corresponding to sand rivers. Still, its real efficiency would depend on river slope, size and bed sediments characteristics, but the k_s+=135 threshold is also questionable and may depend on the Reynolds number. The impact of obstacles (dikes, bridge piles, boulders, etc…) on the drag reduction should also be considered, though it is expected to be negligible as obstacles are relatively sparse in river reaches.

Regarding the environmental issues, several drawbacks can be listed. A first potential drawback concerns the spatial distribution of the flooding risk: the application of present technique should be considered within a global risk management procedure, considering all the hydrological and human processes – and their associated time scales – at the whole river basin scale. A second potential drawback is related to the environmental impact of polyacrylamide, notably on aquatic organisms, injected in the rivers. Anionic polyacrylamide is widely used in irrigation water (Sojka et al., 2001) or mineral extraction water, where its dissemination was commented by Guezennec et al. (2015). But while the injection in sewers in Canada, reported by Hart et al. (2011), concerns about 30 kg per hour and this water goes through a water treatment plant before returning to the river, an injection of 10-20 ppm in a large flooding river of a discharge of about 1500 m^3/s would lead to an injection of about 50-100 Tons of polymer per hour directly in the riverine environment. Present work does not address these effects on the receiving environment, and this technique should be implemented with authorities.

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386 *Table 1. Best-fit Darcy-Weisbach coefficient for 5 selected discharges for water without additives and*
387 *with 20 ppm polymers*

	Plain water				**Water + 20 ppm polymers**			
Discharge Q (m^3/h)	Darcy-Weisbach coeff. (λ)	Water depth (m) @ x~50m	Typical Reynolds number	Froude number @ x~50m	Darcy-Weisbach coeff. (λ)	Water depth (m) @ x~50m	Typical Reynolds number	Froude number @ x~50m
50	0.02	0.22	$6x10^{+4}$	0.36	0.011	0.20	$6x10^{+4}$	0.41
75	0.02	0.30	$7x10^{+4}$	0.34	0.01	0.26	$8x10^{+4}$	0.42
100	0.02	0.35	$8x10^{+4}$	0.36	0.01	0.32	$9x10^{+4}$	0.41
125	0.018	0.40	$9x10^{+4}$	0.37	0.008	0.35	$10x10^{+4}$	0.45
150	0.017	0.50	$9x10^{+4}$	0.31	0.008	0.40	$11x10^{+4}$	0.44

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389

Figure captions

Figure 1. Rheology of water mixture with and without polymers (20ppm) at 24°C.

Figure 2. Photographs of the flume in the smooth (left) and rough (right) configurations.

Figure 3. Backwater curves measured (symbols) and fitted with a constant Darcy-Weisbach coefficient (lines) for a discharge Q=150m^3/h with different concentrations of additives in the smooth bed configuration, with x the streamwise axis oriented towards upstream and x=0 the abscise of the downstream free-fall (the water flows from left to right).

Figure 4. Vertical profiles of timely-averaged streamwise velocity (left) and Reynolds shear stress (right) for two discharges, with 20 ppm and without polymers measured in the smooth bed configuration at x=6.87m.

Figure 5. Backwater curves measured for two discharges without additives and with 20 ppm polymers for the rough bed configuration.

Figure 6. Vertical profiles of timely-averaged streamwise velocity (left) and Reynolds shear stress (right) for two discharges, with 20 ppm and without polymers measured in the rough bed configuration at x=6.87m.

Figure 7. Photograph (top view) of the flow downstream one of the emerging obstacles

Figure 8. Backwater curves measured for a discharge Q=100m^3/h with 20 ppm and without additives in the smooth bed with obstacle configuration.