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Friction and heat transfer in drag-reducing surfactant solution flow through curved pipes and elbows

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ABSTRACT

A study of drag-reducing flow in curved pipes was conducted. In contrast to earlier studies we show that if we use a modified definition of drag reduction that includes only the turbulence effects, we observe indeed the same level of drag reduction in both coiled and straight pipes. More complex results showing reduced drag reduction compared to curved pipes were achieved with elbows. Two elbows of different size and type were tested in turbulent flow of both water and drag-reducing surfactant solution. A more elaborate analysis was conducted for a half-inch threaded elbow with a ratio of curvature radius to diameter of 1.2. The pressure drop and heat transfer were measured in a section downstream from the elbow over a distance of $x/D = 130$ in order to investigate the hydrodynamic and thermal developments of the flow. The pressure drop coefficient of the elbow was calculated for water and a surfactant solution, based on the total increase in pressure drop in the system due to the presence of the elbow. For a larger welded elbow of 6″ diameter some drag reduction was measured for the surfactant solution.

1. Introduction

Several studies have shown that the pressure drop in turbulent flow of water in straight pipes can be reduced by up to about 80% if drag-reducing additives like polymers or surfactants are added in concentrations ranging from a few tens to a few thousands ppm, depending on the additive and the flow conditions. This means that theoretically up to 80% of the pumping power could be saved by the use of additives in straight pipes. An analysis of the possible savings in pumping power and of the problems to be expected in the application of drag-reducing additives in circulation systems like hydronic cooling and heating systems in buildings was presented in Gasljevic and Matthys [1]. Surfactant additives are more promising than polymer additives for practical applications of drag reduction in recirculating systems due to the fact that they do not suffer from the permanent mechanical degradation like polymer additives. Mechanical degradation in its most obvious form appears as a loss of the drag-reducing ability of the solution if the shear stress exceeds a certain critical level. Mechanical degradation of polymer solutions may lead to a complete loss of drag reduction even at the shear stresses normally found in fittings, centrifugal pumps etc, after exposure of the fluid for as little as a few hours or a few days. Surfactant solutions may show a similar loss of drag reduction at high shear stresses, but they recover after the stress is reduced back below the critical level. In other words, the mechanical degradation of surfactant additives is only temporary. The behavior of both polymer and surfactant solutions in straight pipes has been extensively studied and is well documented because the flow conditions can be relatively easily defined in pipes, despite some difficulties due to the non-Newtonian nature of those fluids. In particular the shear stress and the drag reduction level can be readily calculated from measurements of pressure drop in steady and uniform flow conditions.

The situation is more complex in fittings because of the presence of secondary flows and the appearance of flow separations and wakes. In addition, the relatively small lengths where drastic changes in flow are taking place for fittings make accurate measurements of pressure distribution very difficult. The pressure drop over an elbow typically equals the pressure drop in a straight pipe 10 times longer than the stretched length of the elbow, so one can expect much higher shear stresses in the elbow than in the straight pipe. A question that can come to one's mind is whether there is any drag reduction in the fittings and if so, how much. In a typical hydronic cooling or heating system in a building, for example, 10–30% of the total pressure drop in the pipes results from the pressure drop in fittings, and it would be very helpful if one could benefit from drag reduction in those fittings. Another question is how do the fittings affect the flow in the region downstream of the fitting. On the one hand, if the critical stress for the solution is exceeded in the fitting, temporary degradation of a drag-reducing

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surfactant solution will occur and it may then take a significant distance downstream of the fitting for the fluid to recover and to show the full drag reduction again. On the other hand, it could be that only the flow is disturbed, without changes to the fluid micellar structures, i.e. without degradation. In the latter case, although flow redevelopment downstream of the fitting may take up to 150 diameters for viscoelastic fluids, it would be a lesser loss of drag reduction overall than in the case with a temporary degradation of the fluid.

Another issue in many possible applications of drag-reducing additives is the heat transfer reduction, which is coupled with drag reduction. This heat transfer reduction is normally even higher than the drag reduction, e.g. 90% relative to water compared to a drag reduction level of 80%. The heat transfer reduction may be problematic for the implementation of drag-reducing additives in circulation systems which contain heat exchangers. Typically, in such situations one needs to find the means of eliminating the heat transfer reduction in the heat exchangers, most effectively perhaps by intentional degradation [2]. Some other aspects of the behavior of drag-reducing additives in fittings may also influence the heat transfer in heat exchangers. For instance, many heat exchangers (like shell and tube type) imply water flow in tubes. In this type of heat exchangers tubes carrying fluids to which a drag-reducing additive may be applied typically make more passes over the length of the heat exchanger, turning back and forth in 180° bends (essentially 2 elbows in a series). The drag-reducing surfactant solution may temporarily degrade in those bends, and an increased heat transfer will result until the drag-reducing solution recovers from the temporary degradation. Even without degradation in the turn the flow will at least get disturbed in the turn with a resulting increased heat transfer in the developing region downstream of the turn. This can significantly increase the overall heat transfer in the heat exchanger to a level above that of the heat transfer in thermally fully-developed flow.

In this project we studied elbows as they are the most common fittings in hydronic systems, but the results are expected to be relevant for other fittings too. The issues of the flow redevelopment after fittings are closely related to flow development in an entry region [3]. The analysis of the flow of drag-reducing fluids through curved pipes, used here as a basis for the study of flow in elbows, also has importance of its own. Indeed, there are coiled heat exchangers, and also some components of fluid circulation systems with a coiled geometry of curvature radii larger than those for typical short elbows.

1.1. Background

The flow in curved pipes is affected by centrifugal force, which moves the faster fluid from the center line of the pipe towards the outer wall. This results in a transverse secondary motion as the fluid displaced from the wall moves towards the center. The secondary flows in curved circular pipe are seen as a pair of helical vortices. There is extensive literature on the laminar flow of Newtonian fluids in curved pipes and bends, consisting of both analytical and numerical analyses as well as of experimental measurements. Some theoretical foundations were laid down by Dean [4] who introduced a nondimensional number which was later modified and named the Dean number. It combines Reynolds number and relative curvature, and is the only parameter needed to predict the friction coefficient in developed Newtonian laminar flow in curved pipes. Good reviews on this subject can be found in Ward-Smith [5] and Miller [6]. Convenient correlations for the calculation of pressure drop in curved pipes were also offered by Mishra and Gupta [7]. The critical Reynolds number (defining the transition from laminar to turbulent flow) is increased by the increasing curvature of the pipe.

Turbulent flow in curved pipes is too complex for a rigorous analytical approach, even for Newtonian fluids. Models similar to those used for laminar flow at high Dean number do provide good insight into the pressure distribution on the inner and outer wall of the bend however, but cannot provide a realistic velocity distribution. Those models typically include an inviscid core and a viscid boundary layer. Ito [8] correlated a large number of experimental data from various authors to obtain the velocity distribution in the boundary layer and the friction coefficient for fully-developed turbulent flow in curved pipes.

Contrary to pipe bends with large radius of curvature, the elbows found in pipe systems are in most cases short and connected to straight pipes upstream and downstream. In this case, the flow has no time to develop in the bend, but the flow in the portions of the straight pipe upstream and downstream of the bend is affected by the presence of elbow. Analytical procedures for these complex conditions were all developed for ideal fluid with and without rotation. The neglected viscosity of the fluid limited the validity of the results for the velocity field, but the pressure distribution in the bend agrees surprisingly well with experimental measurements. This is valuable information, because regions of adverse pressure gradients can be identified: one on the upstream side of the bend on the outer wall and another one on the downstream side on the inner wall, the second one being more severe. In bends with radius of curvature less than 1.5 tube diameter some flow separation with reverse flow does generally occur. Besides affecting the secondary flow in the bend, the wake region following separation can be a major cause of energy loss in the bend and the pipe section downstream. High shear stresses at the interface of the wake and main flow are very dissipative, but they energize the low energy fluid in the wake and facilitate reattachment. The wake region on the inner wall, which is the main cause of energy dissipation and pressure loss, is located in the region immediately following the bend and extending a few diameters downstream. Some losses are related to the redevelopment of the velocity profile in the pipe downstream of the bend, as well as to the secondary flows in the bend. For a 90° bend of circular cross-section Miller [6] summarized the experimental observations on the distribution of losses between the bend itself and the pipe downstream as follows:

- For a ratio of radius of curvature to diameter of less than 0.8, most of the losses are the result of flow separation and of a wake immediately after the elbow.
- For ratios between 0.8 and 1.5, about 80% of the losses occur in the bend and in the first two diameters after the bend.
- For a ratio of 1.5–3, about 40% of the losses occur downstream of the bend.
- For a ratio larger than 3, the wall friction in the elbow represents the largest portion of the losses.

Ward-Smith [5] offers a conclusion that at curvature ratios smaller than 3, the adverse pressure gradients at the inner wall of the bend, leading to the flow separation, determine the character of the flow in the bend, with the physical length of the bend and the secondary flows becoming less important.

For engineering purposes the main issue of interest is the total increase in pressure drop that an elbow is causing in the pipe system. As mentioned above, it includes both the pressure drop in the elbow itself and the increased pressure drop in the portion of the pipe downstream of the elbow, above the level corresponding to undisturbed developed flow. As is the case for friction coefficient in a straight pipe, the pressure drop coefficient for an elbow gives the total increase of pressure drop due to the elbow when multiplied by the dynamic pressure. Ito [8], Idelchik [9] and Miller [6] provided data on pressure drop coefficients that are particularly valuable for design purposes because of their parametric studies of various factors present in commercial fittings: roughness, condition of the inner corner, and contraction of the flow cross-section for threaded fittings. Ohadi and Sparrow [10] studied the heat transfer in the straight pipe downstream of a bend. Ohadi et al. [11] measured the pressure distribution in the pipe downstream of the bend. For a 90° elbow with hydrodynamically-developed flow at the inlet to the elbow, they found only small differences in pressure gradient and friction coefficient in the pipe downstream of the elbow up to $x/D = 20$, compared to those corresponding to fully-developed flow. Although there is much data on the total pressure drop coefficients for elbows, this may be the only measurement of pressure distribution downstream of an elbow besides that of Ito [8].

As far as we know, there has been no measurement of friction and heat transfer in or downstream of an elbow for drag-reducing fluids in turbulent flow. Weber et al. [12] measured the drag reduction and heat transfer reduction in coiled heat exchangers. In their very extensive and well-documented study they found significantly reduced levels of both drag and heat transfer reductions in coiled pipes when compared with straight pipes, which they explained by the effects of viscoelasticity on secondary flows. The studies of Pak et al. [13–15] for the flow of a solution of a polyacrylamide Separan (Union Carbide Corp.) in a sudden expansion may be also relevant to drag-reducing flow in elbows. Although the former is a very different flow situation, there may be some similarities with elbows, in that there is a flow separation and the appearance of a wake in both cases. The flow visualization experiments of Pak et al. [13] can provide some insight into the effect of viscoelasticity on separation and wakes, which may in turn apply to the flow in an elbow. Some of their findings regarding turbulent flow are that although the wake size was reduced in laminar flow of drag-reducing fluid relative to water, the effect was opposite in turbulent regime; and also that the reattachment length was increased up to 3 times relative to water, with the effect of this increase becoming more important with higher polymer concentration up to 1000 ppm. Pak et al. [14] published their results on pressure loss coefficients for a sudden pipe expansion. For Reynolds numbers up to 10^5 they measured a reduced loss coefficient for polymer solution relative to water. Although the loss coefficient was almost independent of the Reynolds number for water, it increased with Reynolds number for the surfactant solution. Their measurements of heat transfer [15] showed an increase in average Nusselt number of up to 60% for the region from the sudden expansion to $x/D = 225$ downstream, relative to the fully-developed conditions. A maximum Nusselt number appears at x/D ranging from 2.25 to 4.53 downstream from the sudden expansion, depending on the expansion ratio, which is about twice further than for water.

Shah et al. [16] measured the drag reduction in both straight and coiled tubing using various concentrations of a polymer in water, and showed reduced levels of drag reduction in curved tubes compared with drag reduction in straight tubes. Not only was the drag reduction in coiled tubes lower than the drag reduction in straight tubes, but the level of drag reduction decreased with increasing curvature ratio for the coiled tubes. The authors offered correlations to evaluate friction coefficient for the flow of a drag-reducing solution in straight tubes and in coiled tubes with different curvature ratios, but these correlations are limited to a given concentration of a given polymer.

The purpose of our study was to shed some light on the behavior of drag-reducing fluids in curved pipes and fittings.

1.2. Experimental setup and procedure

This study was composed of two distinct parts. Firstly, we studied friction in coiled pipes to gain insight into the basic effect of drag-reducing fluid on secondary flows. Two flexible pipes of inner diameters 12 mm and 2 mm were used to make coils with various curvature ratios (D/d). The pressure drop was measured as a function of velocity in all pipes while still straight before they were coiled, with both water and surfactant solution, for later comparison with the flow through the coiled pipes.

Secondly, two elbows of different size and type were tested: a 1/2″ threaded elbow and a 6″ welded elbow. The flow conditions in a threaded elbow are more complex than in a welded elbow with smooth transitions to the straight pipes, resulting in a higher pressure drop coefficient for the former. Drag reduction is a phenomenon mostly pertinent to skin friction. We never measured any drag reduction in valves, for example, where pressure loss can be seen mostly as form drag. Drag-reducing fluids may therefore show very different levels of drag reduction in elbows and other fittings with different ratios of skin to form drag. An extensive set of tests including both friction and heat transfer local measurements was conducted in the laboratory for a commercial 1/2″ threaded brass elbow. Stainless steel pipe sections were connected both upstream and downstream of the elbow by threaded joints. The roughness of the inner surface of the elbow is estimated to be 0.1–0.2 mm, which is typical for cast fittings. However, the sharp transition from the inner elbow surface to the inner tube surface – about 1 mm of jump – is probably a greater contribution to the increase in pressure drop coefficient above that for a smooth elbow than the elbow surface roughness. Details about the experimental setup and the measuring techniques used in our laboratory tests can be found in Gasljevic and Matthys [17]. The error margin for the friction coefficient is estimated to be 4%, whereas for drag reduction measurements the error margin is reduced to about 2% thanks to the cancellation of systematic errors. Similarly, for Nusselt numbers the error margin is about 5% and for heat transfer reduction about 3%.

Larger welded 6″ diameter elbows were also tested during our field work in a building. Results of this field work can be found in Gasljevic and Matthys [3], together with a detailed description of the measurement techniques used. In that case we measured only the pressure drop coefficient or drag reduction in the elbow. Because of the large diameter of the pipe and the relatively small size of the system leading to short pipe sections (a single building), we could not test a single elbow, but rather had to measure pressure drop over three closely spaced elbows. The distances between elbows were 157 cm and 30 cm. The flow rate was measured with an impeller-type flow meter of 2% accuracy. The pressure drop was measured over a 4.5 m long section including the 3 elbows. For comparison the pressure drop in the straight pipe was also measured over a 5 m long section under fully-developed flow conditions. At every location where pressure measurements were taken, three pressure taps were installed around the circumference of the pipe (with pressure holes carefully drilled and reamed) and these were connected together to average the three pressure measurements at each location in order to reduce the pressure hole error. By averaging the 3 pressure holes at each location the error in the pressure drop measurement must be reduced at least by half. Altogether the error in friction coefficient for the three elbows should be less than 8%.

The surfactant solution used in most tests, both in the lab and in the building, was 2300 ppm of surfactant Ethoquad T-13 (a product of AKZO-Nobel) plus 2000 ppm of NaSal as a counterion, with the molar ratio of NaSal to the surfactant of 2.5:1. It should be noted that after a few months of circulation in our system the properties of the surfactant solution did change somewhat. For instance, the fluid used for the 1/2″ elbow tests was 4 months old and showed a reduced level of drag-reducing ability at low velocities, whereas at higher velocities it maintained a level of drag reduction only a few percent lower than asymptotic drag reduction for a given Reynolds number [18]. The viscosity of that solution was the same as that of water, measured in a capillary tube viscometer at shear rates as low as 10 s^{-1}. The fluid used in the building test for the 6″ elbow was essentially of the same quality.

The Ethoquad solution used in the tests with 12 mm coiled pipes was only about one month old, on the other hand, and showed asymptotic drag reduction at all velocities. That solution showed a viscosity 2 times higher than for water at a shear rate of 500 s^{-1}, measured in a capillary tube viscometer. For one series of runs with the coil of curvature ratio $D/d = 8.6$ we also used a 2 months old solution which still showed asymptotic drag reduction but with the same viscosity as for water, for shear rates as low as 10 s^{-1}. More details on the permanent degradation of these Ethoquad solutions can be found in [19].

For the coiled pipe of 2 mm diameter, a nonionic surfactant (SPE 95285 from AKZO-Nobel) of 2000 ppm concentration was used. This fluid showed a similar drag-reducing ability as the Ethoquad T-13, and no increased viscosity relative to water, measured in a capillary tube viscometer for the shear rates as low as 10 s^{-1}. All tests were done at a temperature of about 25 °C.

2. Results and discussion

2.1. Coiled pipes

Fig. 1 shows some results of our friction tests in curved pipes. All three tests pipes were made from the same semi-rigid plastic pipe with an inner diameter of 12 mm and 8 m long but coiled with 3 different curvature ratios: $D/d = 23$, 15 and 8.6. The surfactant solution used in these runs was made with 2300 ppm of the

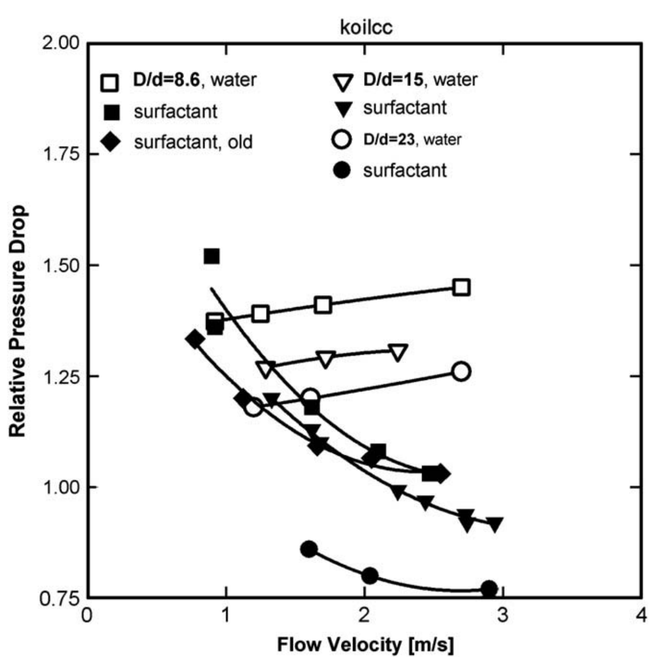

Fig. 1. Pressure drop in coiled pipes for water and a surfactant solution relative to the pressure drop for water in a straight pipe. Three different ratios of coil diameter to pipe diameter D/d are tested. Pipe inner diameter = 12 mm. Two surfactant solutions used; 2300 ppm of surfactant Ethoquad T-13, plus NaSal as a counterion, in a molar ratio to surfactant of 2.5:1. One solution fresh, another two months old.

cationic surfactant Ethoquad T-13 and 2000 ppm of NaSal counterion (molar ratio NaSal:surfactant 2.5:1) in tap water. The results are presented as a ratio of the total pressure drop in the coiled pipe (for either water or surfactant solution) to the pressure drop in the straightened pipe with water flow. For the water flow, we can see in all three coils an increased pressure drop relative to the straight pipe. This increase varies from 15% to 45% depending on the curvature ratio and velocity. For all velocities above 1 m/s the water flow in the coils is turbulent, with the Reynolds number Re above 15,000. (Note that the transition from laminar to turbulent flow in coiled pipes is gradual and for low D/d ratios fully turbulent flow may be postponed to Reynolds numbers as high as 20,000). The water results are in accordance with the predictions by Mishra and Gupta [7].

Most tests with the drag-reducing solution were conducted with a fresh surfactant solution, but one coil – $D/d = 8.6$ – was tested with both fresh and an old solution after a few months of circulation in our closed loop. We see that for almost all runs with the surfactant solution there is some reduction in friction relative to the runs with water. If expressed in terms of the usual drag reduction coefficient

$$\mathrm{DR} = \frac{Cf_{\mathrm{w,t}} - Cf}{Cf_{\mathrm{w,t}}}$$

where $C_{\mathrm{f,w}}$ means friction coefficient of the flow without drag-reducing effects (without drag reduction), and the subscript t refers to turbulent flow, at a velocity of 2.5 m/s we get between 30% and 40% drag reduction (the highest value for the coil with $D/d = 23$). These results are in good agreement with those by Weber et al. [12]. They measured a comparable reduction in heat transfer as well. It is important to note that in the straightened pipe at the same velocity, we measured a much higher drag reduction of 75% (i.e. less than half the normal pressure drop) for the same fluid. This large discrepancy between the straight and coiled pipes has been a topic of inquiry in the past. With the fresh fluid in the most-curved coil ($D/d = 8.6$), there is an increased pressure drop at the lowest velocity ($v = 0.9$ m/s) for the surfactant relative to water. Very likely that is an effect of the increased viscosity of the surfactant solution, about 2 times higher than the water viscosity at a shear rate of 500 s^{-1}. With the old surfactant solution, which showed the same drag-reducing ability as the fresh solution but without the increased viscosity relative to water, we get a lower pressure drop in the coiled pipe than with the fresh surfactant solution and water, even at the lowest flow velocity. Altogether, we can summarize these results overall by noting a significantly lower drag reduction measured in the coiled pipes than in the straight pipes, just as Weber et al. [12] and Shah et al. [16] have found.

Fig. 2 shows calculated values of friction coefficient in straight and coiled pipes for both laminar and turbulent flow, according to Mishra and Gupta [7]. An obvious difference between the straight and coiled pipes is that for the coiled pipes the difference between the friction coefficients in laminar and turbulent flow is much smaller than for the straight pipes. For example, at a Reynolds number of 30,000 the difference in C_{f} between turbulent and laminar flow in for a straight pipe is a factor of 11. For a coiled pipe with $D/d = 100$, the corresponding difference is only a factor of 2.2. If we assume that the effects associated with drag reduction affect only turbulence, the maximum effect of a drag-reducing additive in a coiled pipe can only be to reduce friction coefficient by a factor of 2.2, upon complete laminarization of the flow, and this would still produce less drag reduction than would asymptotic drag reduction in a straight pipe at the same velocity (where a 75% DR corresponds to a 4 times reduction in C_{f}).

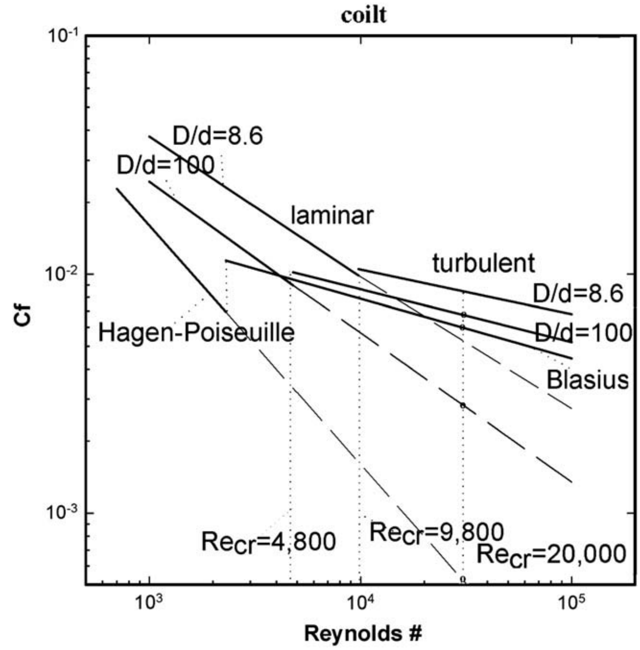

Fig. 2. Calculated values for the friction coefficient of water in a straight pipe and coiled pipes (for two curvature ratios; $D/d = 8.6$ and $D/d = 100$), for both laminar and turbulent flow. Calculations for the coiled pipes according to [7].

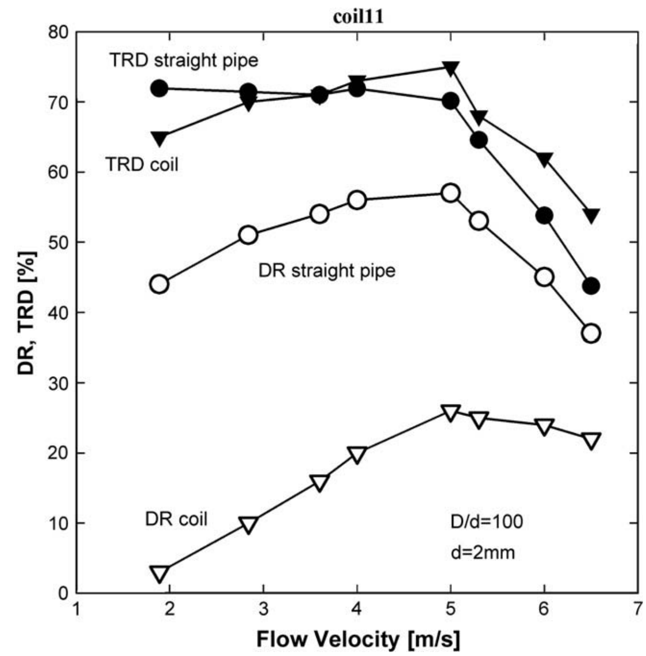

Fig. 3. Friction reduction in the coiled pipe for flow of a surfactant solution using two representations: the usual drag reduction DR, and turbulence reduction for drag TRD. Nonionic surfactant SPE 95285, 2000 ppm, dissolved in water, temperature 25 °C, viscosity same as for water.

Oversimplifying, drag reduction phenomenon appears to be a reduction of turbulence. A better quantification of that effect would be to use as a reference a fully laminarized flow. This quantification parameter which we call "Turbulence Reduction for Drag" is defined as:

$$\mathrm{TRD} = \frac{Cf_{\mathrm{w,t}} - Cf}{Cf_{\mathrm{w,t}} - Cf_{\mathrm{w,l}}}$$

where $C_{\mathrm{f,w}}$ is the friction coefficient of a flow without drag reduction, the subscript t refers to turbulent flow, and the subscript l refers to laminar flow. C_{f} without subscripts stands for the actual friction coefficient of the solution with drag reduction. This parameter is more physically meaningful and stands in sharp contrast to the usual drag reduction parameter given above, which is used in most studies and uses zero friction as a reference. The use of the simpler drag reduction parameter is acceptable when considering flow in straight pipes, because of the large difference in turbulent and laminar friction coefficients for those pipes, and particularly so at high Reynolds numbers. For flow in curved pipes, this is not longer the case, however. For the latter, secondary flows in the laminar regime are responsible for a high level of dissipation, and if we want to compare the reduction in turbulent effects between drag-reducing flows in straight and curved pipes we should use the TRD quantification rather than DR. For more details and some other application of the TRD representation see Gasljevic and Matthys [20].

Fig. 3 shows the results of some friction tests in a coiled pipe of inner diameter 2 mm and curvature ratio $D/d = 100$, using a solution of the nonionic surfactant SPE 95285 at a concentration of 2000 ppm. At a temperature of 25 °C, at which the tests were conducted, this solution shows the same viscosity as water, measured in a capillary tube viscometer at shear rates as low as $10\ \mathrm{s}^{-1}$. The friction coefficients were measured in a coiled and a straight pipe of the same length. The results are presented in terms of both drag reduction and turbulence reduction parameters. As we can see there is a large difference in DR between the straight and coiled pipes, whereas the results expressed in terms of TRD show almost the same values. This means that if we consider only the turbulence effects in both flows, the effects of the drag reduction are the same. It is possible that drag reduction would also affect secondary flows to a minor extent, but when proper values of viscosity were used in the calculations we did not measure significant drag-reducing effects on laminar flow in coiled pipes. The sudden reduction of DR and TRD at velocities higher than 5 m/s is likely due to fluid temporary degradation.

Besides making clear the reason for the apparent large difference in drag reduction effects between coiled and straight pipes mentioned in the literature, this representation is also very useful as an effective predictive tool for the friction one would expect in a coiled pipe. Indeed, one could simply use results in a straight pipe and predict much more accurately the pressure drop for a coiled pipe with the same solution, unlike what is possible with the usual DR parameter.

2.2. Flow after elbows

Flow in an elbow is more complex than flow in a coiled pipe. There are entry and separation effects in addition to the idealized flow similar to that in a coiled pipe. Figs. 4 and 5 show the flow hydrodynamic and thermal developments downstream of a 1/2″ elbow for the flow of water and of surfactant solution (2300 ppm ETHOQUAD T13 plus 2000 ppm NaSal). The results obtained for flow velocities of 1.2 and 5.2 m/s are shown as the ratios of the local friction coefficients and Nusselt numbers to their corresponding values at $x/D = 130$, which can be considered as fully-developed conditions within the stated accuracy of the measurements. The absolute values of drag and heat transfer reductions at $x/D = 130$ are given. Note that the reference values for the calculation of the relative friction coefficient and the Nusselt number differ for water and for the surfactant solution. For example, for 1.2 m/s the reference value for the friction coefficient at $x/D = 130$ is 2 times higher for water than for the surfactant solution because of the 50% drag

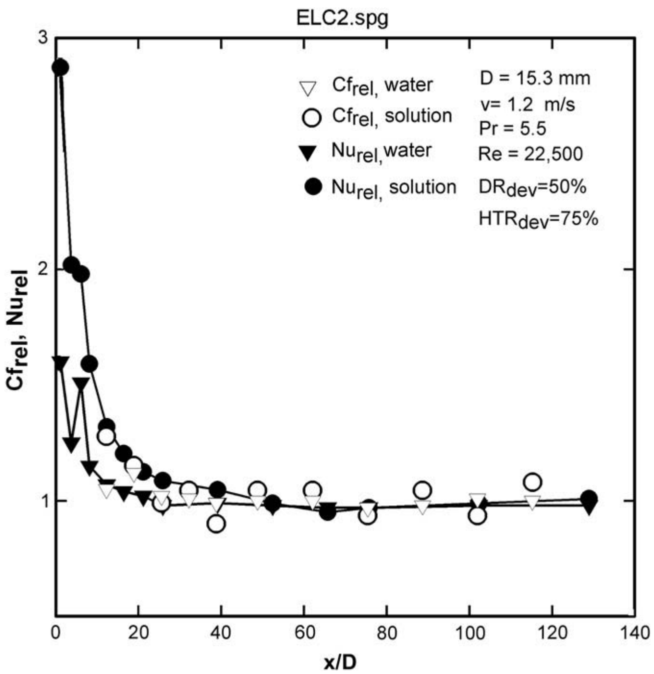

Fig. 4. Nusselt number and Friction coefficient downstream of the elbow, relative to their values at $x/D = 130$. Velocity = 1.2 m/s. Flow hydrodynamically and thermally developed at the inlet to the elbow. Solution: 2300 ppm ETHOQUAD T13 plus 2000 ppm NaSal, in a molar ratio to surfactant of 2.5:1.

reduction in the fully-developed flow. Similarly, the difference in the reference value for the relative Nusselt numbers for water and the surfactant solution is a factor of 4 because of the 75% heat transfer reduction in fully-developed flow. The differences are greater still for 5.2 m/s.

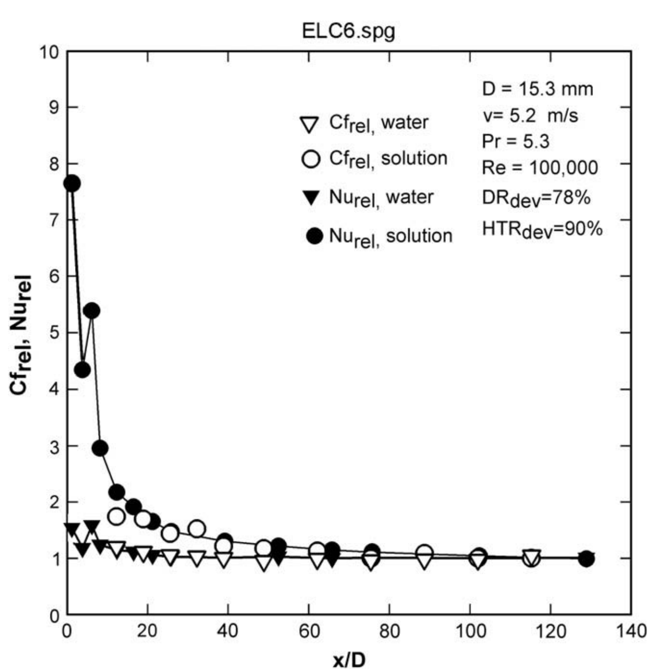

Fig. 5. Nusselt number and Friction coefficient downstream of the elbow, relative to their values at $x/D = 130$. Velocity = 5.2 m/s. Flow hydrodynamically and thermally developed at the inlet to the elbow. Solution: 2300 ppm ETHOQUAD T13 plus 2000 ppm NaSal, in a molar ratio to surfactant of 2.5:1.

From Figs. 4 and 5 one can see that the flow redevelops slower for the surfactant solution than for water. However, for 1.2 m/s (which is a typical flow velocity in circulation systems), at only 20 diameters downstream of the elbow the Nusselt number and friction coefficient for the surfactant solution are already only 15% higher than their corresponding reference (fully-developed) values. For 5.2 m/s the relative values of the Nusselt number and friction coefficient for the surfactant solution 20 diameters downstream of the elbow are still about 75% higher than the corresponding reference values. The slower redevelopment for the higher flow velocity can be attributed to the higher levels of drag and heat transfer reductions at higher flow velocity, which makes the flow more laminar-like. Comparing these results with those achieved with the same surfactant solution but with a much stronger disturbance to the flow in the form of wire mesh inserts [17], one can readily conclude that in the case of the elbow the increased momentum and heat transfer downstream from the elbow should be attributed to flow redevelopment only. In contrast, in the case of wire mesh inserts at higher flow velocities, the solution was temporarily degraded and it took a much longer distance (a few hundred diameters) for the solution to recover from degradation than is necessary for flow redevelopment only. The level of degradation of the surfactant solution by a wire mesh insert was found to be the same for different wire mesh inserts, as long as the pressure drop on the insert was the same. We also found that the level of degradation was very similar even when caused by very different disturbances to the flow, for example both wire mesh inserts and valves, as long as the pressure drops on those degrading devices were the same. In first approximation, this holds for all singular losses typically found in circulation systems, like valves, elbows and other fittings. As the pressure drop on elbows and other fittings typically amounts to a pressure drop over a section of a straight pipe only 10–20 diameters long, it is very likely that those fittings will not cause degradation of even very weak surfactant solutions. The effect of a fitting therefore will be generally limited only to disturbance to the flow, not degradation of the solution.

Note the different nature of friction and the heat transfer measurements. The friction coefficient is calculated from a pressure drop measurement taking place over a finite length of test pipe, and the calculated friction coefficient is therefore an average value for the given segment of the test pipe. The Nusselt number, on the contrary, is calculated from a local temperature measurements and it corresponds to a specific location on the test pipe. Because of the local nature of the heat transfer measurement it is more accurate than the friction coefficient measurement in situations where the measured quantities are changing fast, like in the region close to the elbow. For the same reason, we were able to make the closest heat transfer measurement only 1.2 diameters downstream from the elbow, whereas the closest friction measurement is for $x/D = 12$.

Looking at the measurements of friction and heat transfer downstream of $x/D = 12$, it seems that heat and momentum transfers develop simultaneously. The idea of the simultaneous development is even more convincing if one considers the data presented in Fig. 6, for the flow development after a simpler geometry of the cone entry (with no reattachment, so profiles are smoother). One can assume that the ratio of heat transfer reduction to drag reduction found by Aguilar et al. [21] to be 1.3–1.15 (depending on the flow velocity) for the developed region holds in the developing region as well. This suggests that we can assume a similar development for the friction coefficient for the region $x/D < 12$ where only heat transfer measurements are available. The data for water show a noticeable increase in heat transfer at the third station downstream from the elbow ($x/D = 6.2$). This likely indicates reattachment of separated flow. A similar increase in heat transfer can be seen for the surfactant solution. The location of

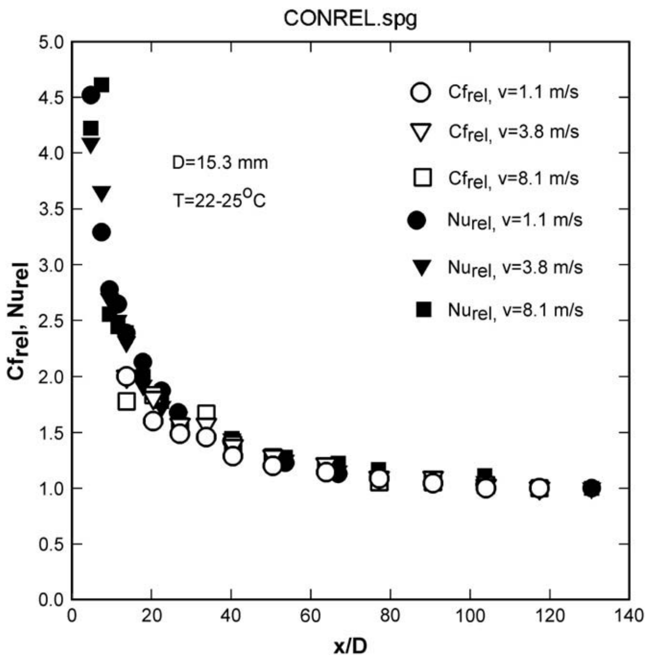

Fig. 6. Nusselt number and friction coefficient downstream from a cone entry, relative to their values at $x/D = 130$. Cone diameters: $D2 = 70$ mm, $D1 = 15.3$ mm; cone length 60 mm. Solution; 2300 ppm ETHOQUAD T13 plus 2000 ppm NaSal, in a molar ratio to surfactant of 2.5:1. Simultaneous hydrodynamic and thermal development of the flow; tube entry at $x/D = 0$, heating starts at $x/D = 3$.

reattachment appears not to depend on the Reynolds number for both water and drag-reducing fluid, but the reattachment distance can be a few times longer for the latter, at least for sudden expansion [13]. In our case we cannot locate precisely the reattachment point because the spatial resolution of the temperature measurements is not high enough, and the difference in the relative increase of heat transfer between water and surfactant solution may be due to a shift in reattachment location.

The heat transfer increase immediately after the elbow is large compared to the fully-developed conditions for the surfactant solution, in fact almost to the level of heat transfer for water. For 5.2 m/s heat transfer is 8 times higher than fully-developed heat transfer for surfactant solution, but after only 10 diameters there is already about 60–70% heat transfer reduction, or a heat transfer about 3 times lower than for water. Although the presence of an elbow in the flow of a drag-reducing solution would in principle increase the heat transfer in heat exchangers, the effect is very local unfortunately, and may not be enough to increase significantly the total heat transfer in heat exchangers where the heat transfer is seriously impaired by drag reduction.

Fig. 6 shows results of flow redevelopment after a cone entry for the same fluid [17], for the purpose of comparison with the flow redevelopment after an elbow. The geometry of the cone entry is a contraction of the pipe diameter from 70 to 15.3 mm over a length of 60 mm. The flow development downstream of the cone entry starts here with an undeveloped flow (assumed to be plug flow), whereas flow at the inlet of the elbow is practically fully-developed both hydrodynamically and thermally (hydrodynamic and thermal flow development started 190 diameters upstream). Although higher increases in the friction coefficient and the Nusselt number relative to the fully-developed conditions can be seen for the flow after the elbow than for the cone entry, this is likely due to the fact that heat transfer measurements were taken closer to the elbow. It can be seen that for the elbow the relative values of friction coefficient and Nusselt number are getting close to unity slightly faster than for the cone entry, which is to be expected as velocity and temperature profiles are not as much affected in the elbow as in the case of flow development from the plug flow.

Fig. 7 shows the pressure distribution in a pipe with an elbow, for the flow of a surfactant solution. A line with constant slope indicates hydrodynamically-developed flow. The dotted line shows the idealized pressure distribution in the system where the total increase in pressure drop due to the presence of the elbow is assigned to a singular point and is calculated by use of the pressure drop coefficient. We can see that the flow development after the elbow takes about 100*D*, a much greater length than for the flow of water which is about 10.

2.3. Friction coefficient for elbows

The most relevant engineering parameter for an elbow is its pressure drop coefficient. It relates the total increase in pressure drop (ΔP) that the elbow imposes on the system to the dynamic pressure ($\rho v^2/2$);

$$k = \Delta P \frac{2}{\rho v^2}$$

Some values of calculated pressure drop coefficient for both water and surfactant solution are shown in Fig. 8, plotted as a function of velocity. The increase in the pressure drop due to the presence of the elbow is calculated by subtracting the pressure drop over a test pipe section of the same length (including the stretched length of the elbow) but without the elbow, and under fully-developed undisturbed flow conditions, from the actual pressure drop over the section of the test pipe containing the elbow. Note that for the measurements with the surfactant solution this means under full drag reduction in the pipe section without the elbow.

Two different lengths of test pipe section were used to measure the pressure drop increase due to the presence of the elbow. In the first case, the first pressure tap was located 10 diameters upstream

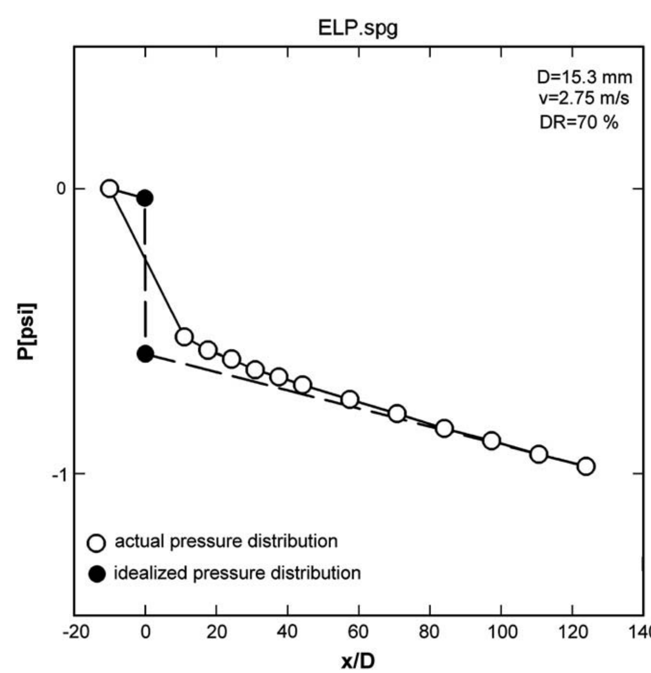

Fig. 7. Pressure distribution in the pipe downstream of the elbow. Besides the actual measured pressure, the idealized pressure distribution is also shown in accordance with the concept of singular pressure drop. Solution: 2300 ppm ETHOQUAD T13 plus 2000 ppm NaSal, in a molar ratio to surfactant of 2.5:1.

of the elbow, and the second one 125 diameters downstream from the elbow. In the second case, a much shorter section of test pipe was used, from 10 diameters upstream to 10 diameters downstream from the elbow. The first case is more relevant for engineering purposes. From Figs. 4 and 5 one can see that at a location 125 diameters downstream from the elbow, the friction coefficient has already reached a steady value corresponding to fully-developed flow, i.e. that the full effect of the elbow is limited to the section of the pipe stretching 125 diameters downstream. A pressure drop coefficient based on the pressure drop increase over this long section of the pipe will maintain its strict meaning. As can be seen in Fig. 8, at the highest velocities the pressure drop coefficient for the surfactant solution is the same as that for water, but at the lower velocities there is up to a 20% increase for the case of the flow of surfactant solution. This means that for design purposes one can assume that there is full drag reduction in the total length of pipes both upstream and downstream of the elbow but no drag reduction in the elbow itself (or even up to a 20% increase of pressure drop in the elbow, for low flow velocities). The results for water are in accordance with available data [6,9] for threaded rough fittings. For a smooth elbow of the same curvature ratio, the pressure drop coefficient would be 2–3 times lower, with a much larger effect of the Reynolds number.

In the second set of results only the section from 10 diameters upstream to 10 diameters downstream was considered, in order to focus on the elbow itself (including any recirculation zone) and to eliminate flow redevelopment in the pipe. The results for water do not differ significantly from the first case with the long pipe section, which is to be expected because the effect of the elbow on the flow of water is practically contained in the region stretching 10 diameters downstream from the elbow, as it can be seen from Figs. 4 and 5. For the flow of the surfactant solution, the difference between short and long pipe sections is more noticeable. At high flow velocities the pressure drop coefficient for the surfactant solution becomes lower than for water. Although considering only the short pipe section misrepresents the total effect on the system, this interpretation of

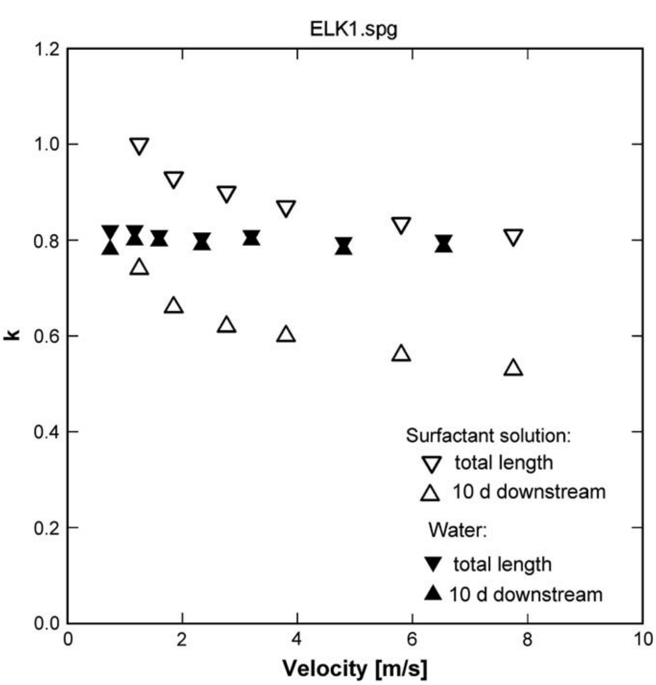

Fig. 8. Pressure drop coefficient for short threaded elbow, for water and surfactant solution: 2300 ppm ETHOQUAD T13, 2000 ppm NaSal, in a molar ratio to surfactant of 2.5:1.

the pressure drop coefficient shows that there is some drag reduction in the section including the elbow and the recirculation zone, but when the whole system is considered it is outbalanced by the increased friction in the redeveloping section downstream (compared to the fully-developed flow).

Analyzing the results, one may say that the dominant losses in a threaded elbow are associated with the flow separation. Although a smooth elbow with the same ratio of radius of curvature to diameter would have 2–3 times smaller losses than treaded elbow, even in the smooth elbow most losses may be due to separation if there is high curvature. It seems reasonable to assume that the difference between the flow of water and drag-reducing solution in the elbow should be attributed to the effect of the drag-reducing quality of the solution on flow separation and reattachment. After separation occurs, the turbulence in the interface layer between the wake region and the main flow (which is a cause of energy dissipation) is at the same time the vehicle for efficient momentum transfer from the main flow to the wake region (which contains low energy particles), enabling reenergizing and reattachment. If the drag-reducing quality of the solution reduces turbulence, it may impede energy transfer to the wake and impede reattachment. Pak et al. [13] indeed found that the reattachment length was increased by a factor of 2–3 in the sudden-expansion flow of a polymer solution, when compared with the flow of water. This may explain the fact that the pressure drop coefficient for the surfactant solution increased with decreasing velocity when one assumes that turbulence is reduced. (It is not an effect of increased viscosity of the surfactant solution at lower shear rates, because this solution showed the same viscosity as water for all shear rates investigated). One may anticipate that the drag-reducing quality of the solution does reduce skin friction in the elbow region without separation, as well as losses related to secondary flows or those due to turbulence in the interface with the wake, while yet increasing the size of the wake at the same time. In larger elbows, the effect of diameter change at the pipe end as well as the elbow surface roughness – which are both responsible for increased separation of the flow – will be much smaller in relative terms, and one should expect smaller losses.

Finally, at the end of this analysis for a 1/2″ elbow, we should point out that even in a smooth coiled pipe only a very small reduction in friction is possible at the velocities which are normally encountered in circulation systems (up to 2 m/s). At a Reynolds number of 30,000 and curvature ratio $D/d = 100$, even with total suppression of turbulence (total flow laminarization or TRD = 100%) we could reduce the friction only by a factor of 2.2, and even significantly less for highly-curved pipes corresponding to curvature ratio of elbows (refer to Fig. 2).

Very different results were obtained with a series of 3 large 6″ elbows welded to the pipes. Here we have elbows with relatively smooth surfaces and, more important, smooth connections with pipes, as well as a moderate curvature radius of 1.5D. As can be seen in Fig. 9, a significant reduction in pressure coefficient is measured with the surfactant solution, relative to water, corresponding to 30–40% drag reduction overall. We do not think that the results would be significantly different for a single elbow. This drag-reducing effect, which was not seen with the small threaded elbow, can likely be explained by the fact that in the smooth less curved elbows, the effect of the flow separation is less prominent. On the other hand, a very high Reynolds number of about 300,000 for velocity of 1.75 m/s, i.e. 127,000 for the velocity of 0.75 m/s, leads to relatively large turbulence, which means a larger potential for reduction in overall friction due to the turbulence reduction from additives. For this large Reynolds number, the maximum turbulence reduction for drag (TRD = 100, i.e. total laminarization) corresponds to about a 4.5 times reduction in friction coefficient for a curvature ratio of

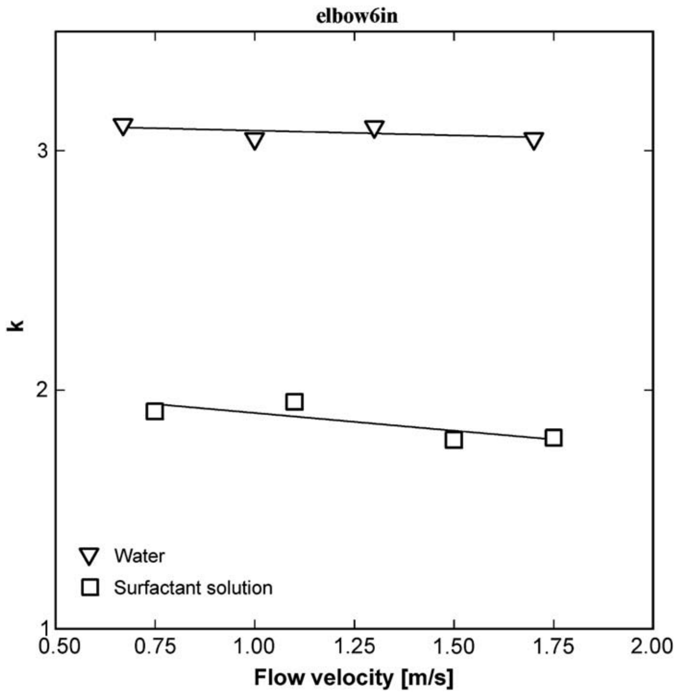

Fig. 9. Pressure drop coefficient for a series of 3 elbows in a 6″ pipe line, for water and surfactant solution (2300 ppm ETHOQUAD T13 plus 2000 ppm NaSal, in a molar ratio to surfactant of 2.5:1). The sections of the straight pipes between elbows are all together 4.36 m long.

$D/d = 8.6$ (extrapolation of Fig. 2). For a curvature ratio of $D/d = 1.5$, the maximum reduction in friction would be lower than that for $D/d = 8.6$, i.e. about a factor of 3. The difference between the maximum possible drag reduction in the 6″ elbows and that actually measured can be attributed to losses due to flow separation. It is important, however, to note that drag reduction is indeed possible in large elbows, because it could contribute noticeably to total pumping power saving in circulation loops such as HVAC systems.

3. Summary and conclusions

The apparent reduction in the effectiveness of drag-reducing additives in coiled pipes can be readily explained by the use of a better parameter for quantification of the drag reduction. If the reduction in pressure drop achieved by drag-reducing additives is compared to the maximum level of reduction corresponding to total flow laminarization (turbulence reduction) instead of the usual drag reduction coefficient, there is indeed no significant difference in the measured effect of drag-reducing additives on the flow through both coils and straight pipes.

The disturbance imposed to a hydrodynamically and thermally developed flow of a drag-reducing surfactant solution by a commercial threaded elbow is rather strong. However, at least for the solutions used in our tests, it appears to be only a disturbance of the flow not affecting the micellar structures of the fluid (i.e. temporary degradation), and it is likely that in most practical applications of drag-reducing surfactant solutions, elbows (and similar fittings) will not cause mechanical degradation of a surfactant solution. The heat transfer and friction coefficients downstream of the elbow develop in a manner comparable to the flow development from a plug flow, although the disturbance imposed on the flow by the elbow is smaller than in the latter case. The heat transfer immediately downstream of the elbow for a surfactant solution is almost as high as for water, i.e. up to 10 times higher than for developed flow, but it decreases to twice the value for developed flow already at $x/D = 20$, continuing to decrease slowly for the rest of the pipe up to $x/d = 130$. At the end of the test pipe ($x/d = 130$), the heat transfer reduction is practically the same as for fully-developed flow (about 90% for this fluid). The friction coefficient appears to follow closely the development of heat transfer if both are expressed in relative terms based on the corresponding values at the end of the test tube ($x/D = 130$) as a reference.

The pressure drop coefficient for the 1/2″ threaded elbow for the surfactant solution is practically the same as for water i.e. about 0.8, except at low velocities (at a velocity of 1 m/s there is about a 25% increase in pressure drop coefficient for the surfactant solution compared to water). These experimental results can be interpreted as the appearance of some drag reduction in the elbow (including the recirculation zone) which is outbalanced by less than full drag reduction in the pipe downstream of the elbow, due to flow redevelopment over a long hydrodynamic entry length.

A sharp cast elbow with threaded joints causes high losses in the flow of water. A pressure loss coefficient about 3–4 times higher is to be expected for that kind of elbow than for a smooth elbow with undisturbed transition to the straight pipes. Even in the smooth elbow, for a curvature radius to diameter ratio of 1.3, most of the losses are due to flow separation on the inner wall at the downstream end of the elbow. Consequently, the increased pressure drop coefficient seen for our threaded elbow for the surfactant solution can be attributed to the effect of elasticity on flow separation and reattachment. As the elasticity of a surfactant solution reduces turbulence, it may also reduce energy transfer to the separation region and impede the reattachment of the flow, especially at low Reynolds numbers where turbulence is reduced anyway.

For the smooth welded elbows of 6″ nominal diameter, about 40% drag reduction was measured. The difference with the small threaded elbow is in the large Reynolds number and lesser susceptibility to flow separation. A very large Reynolds number leads to a larger difference in friction for laminar and turbulent flows, which means a possibility for more drag reduction to take place. The losses due to flow separation (which may not be affected by drag-reducing additive) are indeed present in a smaller proportion in the large smooth elbow than in the sharp treaded elbows, if not completely eliminated.

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