# DRAG REDUCTION BY POLYMER ADDITION IN SINGLE AND TWO-PHASE GAS-LIQUID FLOWS IN PIPELINES

# Vanessa Cristina Bizotto<sup>1</sup>, vanessa@cepetro.unicamp.br Diogo Melo Paes<sup>1</sup>, diogopaes10@hotmail.com Edvaldo Sabadini<sup>2</sup>, sabadini@iqm.unicamp.br Fernando de Almeida França<sup>1</sup>, ffranca@fem.unicamp.br LabPetro/UNICAMP<sup>1</sup>, IQ/UNICAMP<sup>2</sup>

Abstract. Turbulence mechanisms, as the eddies formation frequency and size, promote energy dissipation that appears as pressure drop in pipe flows. Adding minute amounts of polymers – ppm - of high molecular weight to the solution can lead to the reduction of the viscous dissipation. The formed macromolecules interact with the eddies, cause the eddies coherence breakdown, damp the energy transport and reduces the pressure drop. This phenomenon is known as the hydrodynamic drag reduction (DR, for short). Thus, for a given pipe flow rate there is decrease in pressure head, which is a desired operating strategy when transporting liquids. Studies on the hydrodynamic drag reduction in polymeric systems have been carried out in collaboration by the Chemistry Institute and the Petroleum Laboratory – LabPetro, UNICAMP. These studies have allowed microscopic approaches to the engineering scales, tackling the most usual processes – single phase flows, as well as gas-liquid two-phase flows in pipelines, which are quite common in the chemical and the petroleum industries. Tests conducted in the Chemistry Institute comprised over-the-bench experimentations made with a rotational double-gap type rheometer. These quick performed tests used small amount of polymers, and provided information on the additive concentration, the drag reduction and the solution mechanical stability along a turbulent shearing process. The results indicated that 17% is the limiting drag reduction achieved when a 2 ppm aqueous solution of polyacrilamide - PAM – was tested. These tests, besides giving preliminary estimations, are limited in terms of engineering application due to the low shearing rates applied by the viscometer. The tests performed at LabPetro comprised pressure drop measurements in actual pipe flows, both water single and air-water two-phase flows, using the previous knowledge acquired with the viscometer tests. In the former case, the Prandtl-von Karman map has been drawn to show the %DR in terms of the friction factor reduction for the Reynolds number in the  $2x10^4$  to  $10^5$  range. Single phase flows attained up to 30% DR with commercial PAM (FA 920), depending on the polymer concentration. Preliminary results of DR tests performed with air-water flows, in different flow patterns - stratified-wavy and slug flows, are shown. To infer the air-water flow pattern, high speed filming was used.

Keywords: drag reduction, turbulent flow, single and two-phase flow

# **1. INTRODUCTION**

In 1948 Toms reported that very dilute high-molecular weight polymer solution (usually considerably fewer than 1000 parts of million, ppm) could cause large reductions in the turbulent pipe flow pressure drop in comparison to that obtained with the pure solvent at the same flow rate (Virk *et al.*, 1967). This phenomenon is known as hydrodynamic drag reduction (DR). Applications of this phenomenon are found in various areas, mainly in liquid transportation by pumping processes. The transportation of crude oil in the Alaskan and the Norwegian pipelines are actual examples. Polymers ranging in concentration from 5 to 25 ppm have been used in up to 1.20 m diameter pipelines. The drag reduction is mentioned to be as high as 28%. Under laboratory conditions the percentage can go up to 80% (Sellin and Hoyt, 1982; Kulicke *et al.*, 1989).

There have been for some decades drag reduction studies on several solvent/additive systems, including dilute solutions of high molecular weight, soluble polymers, surfactants and micellar systems, suspensions of insoluble particles such as fine grains or fibers, and polymer solutions mixed with soaps or fibers (Morgan and McCormick, 1990). Among these, the most effective drag-reducing polymers, in general, possess a flexible linear structure with a very high molecular weight. A high molecular weight water soluble polyacrilamide (PAM), which has been widely used as a drag reducer in aqueous systems, was adopted in our study. For organic systems, oil-soluble polymers, polyisobutylene (PIB) and polystyrene (PS) were commonly used. PIB is the only polymer, which has received some acceptance as a drag reducing additive for crude oil (Ram *et al.*, 1967; Choi *et al.*, 1999; Kim *et al.*, 2005).

Modeling DR in macromolecular systems is necessarily complex, as both turbulence mechanisms and the extremely dilute nature of the solutions involved have to be taken into account. Although the existence of DR has been recognized for many years and the macro-scale mechanisms are well characterized, a molecular understanding of the role of added polymer in DR processes is still primitive (Morgan and McCormick, 1990). There are many different theories about the DR phenomenon based on molecular approach considerations. Consensually, the theories assume that the added macromolecules under high shear undergo dynamic chain elongation absorbing the energy of the dissipative eddies formed in the flow (Kim *et al.*, 1993). According to Tabor and De Gennes (De Gennes, 1990), the polymer affects the

evolution of the vortices cascade, storing up some of the turbulence energy in the chain. This way, the macromolecules prevent both loss of fluid kinetic energy and the formation of eddies which results in DR (Kulicke *et al.*, 1989).

Practical studies involving this phenomenon are generally performed in pipe flows, where the degree of DR (%DR) is related to the magnitude of the pressure gradient along the tube. Although these experimentations provide realistic tests of polymer induced DR, pipe flow systems are usually large, the instrumentation is costly and the measurements are both solution and time consuming. Recently, Nakken *et al.* (2001) reported DR results with accuracy and reproducibility better than  $\pm 2,5\%$  using a rheometer containing a double-gap cell. The liquid sample fills the two gaps formed between the inner and outer rotor cylindrical surfaces and the stationary cup. The centrifugal force increases from the inner to the outer gap and creates differences in the flow field. At low speed, Couette and Searle flows occur in the inner and outer gap, respectively. Increasing the angular speed, a first instability - Taylor flow - appears in the outer gap. The Taylor flow, (see Fig. 1.a in 2.1), consists of two counter-rotating pairs of vortices overlapped with the Searle flow (Groisman and Steinberg, 1996).

The onset condition for the Taylor vortices is clearly marked by a sudden increase in the shear stress. The flow field eventually becomes turbulent if the speed is further increased. Under such hydrodynamic conditions, the drag reduction effect caused by the macromolecules in the solution can be directly calculated by the ratio between the solution ( $\tau_p$ ) and the pure solvent ( $\tau_s$ ) measured shear stresses, (Eq. 1):

$$\% DR = \left(\frac{\tau_s - \tau_p}{\tau_s}\right) x 100 \tag{1}$$

Drag reduction by dilute polymer solutions in turbulent pipe flows is by now well known and there are recent experimental studies on the subject (Al-Sarkhi and Hanratty, 2001; Kulik, 2001; Zhang *et al.*, 2005). The rough wall case is of great interest when the focus is on the desired practical applications of drag reduction. Moreover, they offer the possibility of inferring features of the wall-flow structure from relatively simple friction factor measurements. Some propose that the drag reducing agent molecules are most active in the "buffer layer", in other words, they act mostly in the flow region between the viscous sub-layer near the pipe wall and the turbulent core at the pipe center region. The turbulent eddies formed in the near-wall region as "streaks", periodically rise up thorough the buffer zone and are ejected as "bursts" into the turbulent core. During this bursting process the energy dissipation in the pipe flow takes place. It is suggested that macromolecules somehow interfere with the bursting process through the turbulence coherence breakout (Kulicke *et al.*, 1989). The net result is the reduction of the turbulence production in the core flow region, affecting the turbulent kinetic energy and dissipation rates. From a practical standpoint these mechanisms appear as a lower pressure drop or DR.

For pipe flow the experimental data are usually presented relating two scaling parameters, the friction factor (f) and Reynolds number (Re), as the classical Moody Diagram (f vs Re) or the Prandtl-von Karman map  $(1/\sqrt{f} vs \text{ Re}\sqrt{f})$ . The friction factor and the Reynolds number are defined by:

$$f = \frac{D}{2\rho U^2} \frac{\Delta P}{L} \tag{2}$$

$$Re = \frac{\rho UD}{\mu}$$
(3)

where *D* is the pipe diameter (m);  $\Delta P$  is the pressure drop (Pa);  $\rho$  is the density (kg m<sup>-3</sup>); *U* is the mean fluid velocity (m s<sup>-1</sup>); *L* is the pipe lenght (m) and  $\mu$  is the dynamic viscosity (Pa s).

The drag reduction percentage (%DR) for pipe flows is the ratio between the solution to the pure solvent pressure gradient  $(\Delta P_p/\Delta P_s)$  or between friction factors:

$$\% DR = \left(1 - \frac{\Delta P_p}{\Delta P_s}\right) x 100 = \left(1 - \frac{f_p}{f_s}\right) x 100 \tag{4}$$

In pipe flow of Newtonian fluids, the drag reduction appears only in turbulent flow, *i.e.* for Re > 2300; if the flow is laminar the turbulence mechanisms lack and there is no influence of the drag reducing agents (Manfield *et al.*, 1999).

The effect of drag reducing agents in multiphase mixtures, gas-liquid, liquid-liquid or even liquid-solids, has received relatively little attention. Oliver and Young Hoon reported the first experiments on drag reduction in gas-liquid flows in 1968. They measured the DR in various gas-liquid flow patterns mixing air to Polyethylene oxide (PEO) aqueous solutions and air. They found out that in slug flow pattern the liquid exhibited considerably less re-circulation,

the mixing process that cause the gas dispersion. On the other limiting condition, the high gas flow rate forming the annular flow, the wave formation was damped, resulting in a smoother liquid film (Manfield *et al.*, 1999).

In multiphase systems the benefits of the use of DR agents are on the extreme limit, not only because multiphase flows cause higher pressure drop compared to single phase flows but due to the its ubiquitous nature. In oil production networks, for instance, the gas-liquid flow is almost inevitable: the reservoir is always producing multiphase mixtures; in pipelines, even after a pre-processing and separation treatment, where water and solid particulates are taken out, lower *in-situ* pressure and temperature can cause gas liberation or liquid condensation. Moreover, in production or transportation pipelines, the distance between the wellhead and the gas-liquid separator can be as short as a few meters or as long as 100 km. A high-pressure drop due to multiphase flows often imposes a significant backpressure on the reservoir and reduces the production.

The increased momentum transportation in gas-liquid flows is due to the complex flow topology and the interfacial transfer. Different flow regimes occur according the phase concentration. In horizontal pipe flows there are: (1) the stratified flow; (2) the stratified-wavy flow; (3) the plug flow; (4) the slug flow and (5) the annular-mist flow and the (6) bubbly flow. Flow regimes depend on many factors, besides the phase concentration: flow rates; the phases physical properties such as density, viscosity, and surface tension, pipe shape, size and orientation, flow conditions, as pressure, and others. When both the gas and the liquid flow rates are very small, the stratified flow is formed. The phases flow at different velocities separated by a smooth interface between them. The stratified-to-plug transition occurs when the liquid flow is increased and plugs of gas flow intermittently, surrounded by long liquid slugs. Alternatively, if the gas flow is increased, the stratified interface becomes wavy; the waves grow up to the point of creating a "bridge" between the liquid interface and the pipe upper wall. An intermittent - or slug flow - is formed: long liquid and elongated gas bubbles appear in succession in the pipeline. The liquid slugs and elongated bubbles are comparable in size, or even much larger, to the pipe diameter. At higher gas flow rates, partial phase segregation takes place, as the liquid flows mostly on pipe rim and the gas is at a much higher velocity in the pipe center region. The flow regimes are annular or mist-annular, both characterized by wavy interfaces and dispersion of both liquid and gas in the gas and liquid "continuous" region. Bubbly-flow regime is characterized by the dispersion of small gas bubbles in the continuous liquid phase, occurring when the liquid flow rate is large and the gas flow rate is small. In every situation mixing, collisions, turbulent dispersion and entrainment mechanisms happen. Recently, studies are appearing in the literature showing that, besides reducing the pressure drop, the drag reducing agent can also affect the flow topology as the mentioned mechanisms are influenced, and then move the "boundaries" that separate the various flow patterns (Al-Wahaibi et al., 2007). Also, Wilkens and Thomas (2007) reported interfacial roughness dampening in stratified flow disturbance waves, claimed to be the main mechanism triggering the onset of slug flow.

The objectives of the present work were to investigate the DR caused the addition of polymers to single and twophase gas-liquid flows in a horizontal pipe. The percentage of drag reduction was measured for different polymer concentrations in water flows after preliminary over-the-bench experimentations made with a rotational double-gap type rheometer. These tests collected information on the additive concentration, the drag reduction and the solution mechanical stability along a turbulent shearing process. In sequence, pressure drop measurements in actual pipe flows, both water single and air-water two-phase flows have been performed. Air-water test flows were exploratory in the sense that only a few data on slug and annular-wavy flow patterns pressure drop been acquired. A high-speed video camera was used to infer the two-phase flow patterns before and after the polymer injection. However, neither image comparisons were made nor additional dynamic analyses of the in-situ pressure or pressure drop have been performed to assess the flow topology signature. The %DR was measured having the single phase and the two-phase solution flow as a benchmark in every case.

# 2. EXPERIMENTAL SETUP

#### 2.1. Experimental apparatus

Rheological measurements were performed with a Haake Instruments RheoStress 1 rheometer at IQ/UNICAMP. Measurements were made using a double-gap geometry (Taylor-Couette cell) (Fig. 1.b) with the active rotor height, H = 55.0 mm and with radii  $R_1 = 17.75$  mm,  $R_2 = 18.35$  mm,  $R_3 = 20.99$  mm and  $R_4 = 21.7$  mm. The double-gap cylindrical cell placed in the liquid rotate about the axis of the cylinder while the sample holder is stationary. The volume of liquid sample (11.5 ml) was kept fixed in all the experiments and the temperature of the system was maintained at 25.00 ± 0.01 °C by a constant temperature circulating apparatus. The maximum speed of rotation for this instrument is  $\Omega = 1,200$  rpm (revolutions per minute) which corresponds to a maximum geometrically averaged shear rate of 3,900 s<sup>-1</sup>. The shear viscosity of the solutions was measured using an Ostwald viscometer – 50, the density of the solutions was measured using a plate surface tension of the solutions was measured using a plate surface tension et (Sigma 701 System Unit).



Figure 1. a) Schematics of the double-gap cell and Taylor flow in outer gap (adapted from Nijman, J. Taylor Flow in Concentric Cylinder System, technical note, Thermo Fisher Scientific); b) schematics and dimensions.

For single and two-phase air-water pipe flows the experimentations were conducted in a horizontal flow loop at LabPetro/UNICAMP. The flow loop is shown schematically in Fig. 2.



Figure 2. Pipe flow set-up schematics.

The stainless steel pipe had an inner diameter 0.01566 m and 7 m of total length, including the inlet, development, test, visualization and exit sections. Two carefully calibrated differential pressure transducers with a very low response time (Validyne) measured the pressure drop. Their signals were acquired and stored by a National Instruments board connected to a desktop computer. The signals were acquired during 13 seconds at a 400 Hz sample rate and processed by the LabView software. The complete flow set-up comprises a storage tank, a pump, a frequency inverter to drive the pump, a shell-and-tube heat exchanger, a flow viewing box and additional instrumentation, as a main Coriolis mass meter and temperature and pressure sensors.

The stock solution (ppm of PAM in water) was stored in 10 liters pressurized tank to be injected in the flow loop just after the horizontal inlet section to avoid the strong degradation process caused by the intense shearing inside the centrifugal pump. The polymer solution was measured by a small size Coriolis mass meter before being injected in the main flow through a hole at the bottom of the pipe. In each run the drag reduction solution was added steadily in the flow, driven by the pressure in the tank and controlled by a needle valve. When air-water flows were tested, the air was mixed to the water flow through a special device, whose connections were chosen in accordance with the desired flow pattern.

The stock solution was added to the main flow after a previous estimation made with a software spread-sheet, taking into consideration the concentration of stock solution, the real-time flow rate in the test section and the desired polyacrilamide concentration in the main section.

Friction factors vs Reynolds number (f vs Re) curves for pure water were generated, accordingly to the Moody diagram, as a calibration procedure diagram before the tests on %DR were performed. The calibration data could be reproduced in different days. After that, studies with the drag reducers were started.

A viewing box made from acrylic was placed around a transparent portion of the test section to facilitate fast image recordings of two-phase flows before and after addition of the polymer. The box was located at the end of the test section. All the single and two-phase flow patterns were considered to be fully developed at the test and visualization sections, as the beginning of the test section was at a distance 200 L/D from the water and air injection point. A Photron high-speed camera (Photron 1024 PCI) with a Navitar 50 mm lens was used to capture flow images at 1000 frames per second, the shutter speed set to 1/10000 s.

#### 2.2. Polymer solutions (drag reducers)

Samples of a high grade PAM (BDH) and a commercial PAM (FA 920, Floerger) with nominal molecular weights  $5x10^6$  and  $6x10^6$  g mol<sup>-1</sup>, respectively, were weighed and were sprinkled over a large area of water to avoid clumping of the particles. At 3 hours intervals, during two days, the solutions were gently stirred using a glass rod to avoid polymer degradation. Then, the stock solution was prepared, diluting it to the required polymer concentration. When the pipe flow experimentations were carried out, stock solutions were prepared the week before and kept in a tank under gentle mechanical stirring. Water from a Millipore Milli-Q Gradient filtration system was used for the rheometer tests. Regular tap water was used in the pipe flow tests. Due to the high accuracy required the stock solutions were prepared by weighing the water and the polymer within  $\pm 1$  mg.

Table 1.	. Test fluids	properties	at 25°C.
----------	---------------	------------	----------

Properties	Polymer solution	Water
Density (kg m <sup>-3</sup> )	997	996
Viscosity (N s m <sup>-2</sup> )	$8.9 \text{x} 10^{-4} - 1.9 \text{x} 10^{-3}$	$8.9 \times 10^{-4}$
Surface tension (mN m <sup>-1</sup> )	73.3	73.0

#### 3. RESULTS AND DISCUSSION

#### 3.1. Effect of polymer concentration on single phase flows

The experimentations began with the rotational rheometer %DR measurements. The objectives were two-fold: a first evaluation of the active range of polymer concentration and the solution stability analysis under continuous shearing. After identifying a working concentration range encompassing the maximum %DR condition – PAM concentration when the %DR is maximized, the pipe flow tests were performed.

Regarding the rheometer tests with the high grade BDH-PAM, a 16%DR maximum was obtained with a 2 ppm concentration. At higher concentrations there is a strong reduction of the %DR due to considerable increase of the shear viscosity of the polymer solutions. Cowan *et al.* (2001) mentioned that in Poiseuille flows (capillary tube) the maximum %DR is about 40% when testing high grade PAM; in drop impact ("splash") experimentations, another over-the-bench technique to appraisal the DR in liquid systems, Bizotto (2008) found a limiting value of 55%DR.

The rheometer tests carried out with the commercial FA920-PAM gave 20%DR maximum at 40 ppm concentration. Nevertheless, a 17%DR value was reached for 10 ppm polymer concentration. A cost-benefit analysis should be performed to establish the turning point in terms of maximizing the %DR at a lower cost, or concentration, for every liquid transportation system under consideration.

When the two curves for the high grade and the commercial PAM are compared, in terms of %DR vs ppm, it is clear that the BDH-PAM solution has the steepest gradient and hits a saturation condition at the very low 2 ppm concentration. The FA920-PAM promotes a higher degree of %DR, but it grows exponentially and the %DR saturation condition was not reached even for concentrations as high as 40 ppm (20%DR).

The pipe flow Prandtl-von Karman map was constructed for the BDH-PAM and FA920-PAM and appears in Fig. 5.a. It shows that a maximum %DR occured at  $Re = 10^5$ . The next step was to do experimentations varying the polymer concentration at this fixed Re number, that was the highest flow rate that could applied in pipe flow tests. The results are shown in Figure 5.b in terms of f vs concentration. The FA920-PAM produced 37%DR at 15 ppm concentration and seemed to be reaching a saturation point. At 15 ppm concentration the BDH-PAM produced 25%; at 18 ppm it levered to 32%DR without an indication that a %DR saturation point was close to be reached. It was somewhat surprising to find out that the commercial FA920-PAM solution yield the highest %DR in the full range of polymer concentration

used in the tests. Moreover, the high grade BDH-PAM did not achieved a %DR saturation point even its concentration was taken to 18 ppm.



Figure 4. %DR vs ppm concentration for BDH-PAM and FA920-PAM. Rheometer at maximum shear rate,  $\Omega = 1200$  rpm. The dashed lines are not fitting equations.



Figure 5. a) The Prandtl-von Karman map for BDH-PAM e FA920-PAM at 10 ppm polymer concentration; b) Friction factor vs ppm concentration for BDH-PAM and FA920-PAM at  $Re = 10^5$ .



Figure 6. %DR vs ppm concentration for BDH-PAM at various Re.

Figure 6 shows the BDH-PAM %DR vs concentration curves having the Re as a parameter. As expected, the %DR growing rates are directed related with the Reynolds number or flow rate, as lower Re produced lower %DR at a fixed concentration. Moreover, at lower Re a trend towards a %DR saturation happened at lower concentration: at  $Re = 4x10^4$  the maximum %DR took place with 25 ppm concentration.

## 3.2. Drag reduction in gas-liquid two-phase flows

The appraisal of %DR in two-phase flows in by far more complex than in liquid single phase flows. Two phase flows may have different phase arrangements, the so-called flow patterns, according operational conditions, fluids properties, system configuration and dimensions, and flow nature, etc. The polymer addition may cause some %DR in every flow pattern but may change the flow pattern topology along the pipe, the flow characteristics or even the two-phase pattern formation as well, as mentioned previously.

In this work only preliminary data have been taken to gauge potential prospects and to establish some limiting parameters and system configurations for future detailed data measurements. The %RA was measured for two of most usual horizontal flow patterns found in oil production: the intermittent or slug flow and the annular flow. When the slug flow was tested, the mean void fraction was roughly 18% to 20%; when the two-phase pattern was the annular flow, the mean void fraction was always above 90%. The FA920 PAM solution was added to the flow after the air-water mixer, which meant that the flow pattern was established previously the DR injection. Due to the short pipe length between the polymer injection position and the pressure drop metering section (Fig. 3) it is unlikely that any major changes in flow pattern or characteristics have been caused. Fast images of the slug and annular flows, with and without the addition of polymer, have been recorded during 4 s at 1000 frames/s with a 10000 s<sup>-1</sup> shutter speed, using backlighting. Samples appear in Fig. 7. As expected, a careful analysis of the fast film shots did not reveal any major changes in flow topology. When planning future measurements, besides increasing the horizontal pipe total length, pressure taps will be added to allow for the measurement of the instantaneous static pressure. Statistical and frequency domain analysis of the local pressure may reveal subtle changes in flow dynamics that are difficult to capture using the fast images.



Figure 7. Two-phase flow patterns (a) intermittent or slug flow and (b) annular flow.

In Table 2 there are the %DR values measured in the slug flow pattern for various FA920 polymer concentrations and different mixture velocities. When the annular flow was tested, a limiting 17%DR was measured.

Flow pattern	Polymer	Air flow rate	Water flow rate	$\Delta P$ w/polymer/	% DR
	concentration (ppm)	(Kg/s)	(Kg/s)	$\Delta P w/o$	
				polymer	
Slug	11	7.5x10 <sup>-5</sup>	0.41	0.333/0.310	7
Slug	44	7.5x10 <sup>-5</sup>	0.41	0.333/0.280	16
Slug	45	6.9x10 <sup>-5</sup>	0.28	0.170/0.158	7
Slug	67	6.9x10 <sup>-5</sup>	0.28	0.170/0.157	7

Table 2. %DR in air-water slug flows, FA920 PAM.

# 4. CONCLUSION

The use of a "double gap" rheometer to measure the %DR in aqueous polymeric solutions was shown to be an accurate and reproducible technique. The experimentations performed with this "over the bench apparatus" were fast and used far less polymer than pipe flow tests. However, if the technique is helpful in providing the %DR for a very fine polymer concentration range, a correlation with pipe test results is needed because of the difference in the turbulence characteristics. The rheometer tests with 40 ppm of commercial PAM (FA 920) reached a maximum 20%DR; in the pipe flow a maximum of 40%DR was measured with 15 ppm concentration of the same polymer in pipe but with polymer. Promising preliminary results were also obtained with air-water two-phase flow. These more complex flows, however, required more complex tests and analysis, as the phase distribution and the flow dynamics may change because of the polymer addition. Moreover, the various flow patterns may have particular behavior in terms of the %DR.

#### 5. ACKNOWLEDGEMENTS

The authors would like to thank PETROBRAS, CNPq and FAPESP for providing financial support to this work.

## 6. REFERENCES

- Al-Sarkhi, A., Hanratty, T. J., 2001, "Effect of drag-reducing polymers on annular gas-liquid flow in a horizontal pipe", International Journal of Multiphase Flow, Vol.27, pp. 1151-1162.
- Bizotto, V. C., 2008, "Redução do atrito hidrodinâmico em soluções de polímeros e dispersões de partículas coloidais", Tese de Doutorado, UNICAMP, Campinas.
- Choi, H. J., Kim, C. A., Jhon, M. S., 1999, "Universal drag reduction characteristics of polyisobutylene in a rotating disk apparatus", Polymer, Vol.40, pp. 4527-4530.
- Cowan, M. E., Garner, C., Hester, R. D., McCormick C. L., 2001, "Water-soluble polymers. LXXXIII. Correlation of experimentally determined drag reduction efficiency and extensional viscosity of high molecular weight polymers in dilute aqueous solution", J. Appl. Polym. Sci., Vol.82, pp. 1222-1231.
- De Gennes, P. G., 1990, "Introduction to Polymer Dynamics", Ed. Cambridge University Press, UK.
- Duangprasert, T., Sirivat, A., Siemanond, K., Wilkes, J. O., 2008, "Vertical two-phase flow regimes and pressure gradients under the influence of SDS surfactant", Experimental Thermal and Fluid Science, Vol.32, pp. 808-817.
- Groisman, A., Steinberg, V., 1996, "Couette-Taylor flow in a dilute polymer solution", Phys. Rev. Lett., Vol.77, pp. 1480-1483.
- Kim, O. K.; Choi, L. S.; Long, T; McGrath, K.; Armistead, J. P.; Yoon, T. H., 1993, "Unusual complexation behavior of poly(acrylic acid) induced by shear", Macromolecules, Vol.26, pp. 379-384.
- Kim, C. A., Choi, H. J., Sung, J. H., Lee H. M., Jhon M. S., 2005 "Effect of solubility parameter of polymer-solvent pair on turbulent drag reduction", Macromol. Symp., Vol.222, pp. 169-174.
- Kulicke, W.-M., Andreis, M., Gräger, H., Koening J. L., Köter M., 1989, "Advances in Polymer Science, Polymer Characterization/Polymer Solutions", Vol.89, Ed. Springer-Verlag, Berlim, pp. 1-45.
- Kulik, V. M., 2001, "Drag reduction change of polyethyleneoxide solutions in pipe flow", Exp. Fluids, Vol.31, pp.558-566.
- Manfield, P. D., Lawrence, C. J., Hewitt, G. F., 1999, "Drag reduction with additives in multiphase flow: a literature survey", Vol.11, pp 197-221.
- Morgan, S. E., McCormick, C. L., 1990 "Water-soluble copolymers. XXXII: Macromolecular drag reduction. A review of predictive theories and the effects of polymer strutucture", Prog. Poly. Sci., Vol.15, pp. 507-549.
- Nakken, T., Tande, M., Elgsaeter, A., 2001 "Measurements of polymer induced drag reduction and polymer scission in Taylor flow using standard double-gap sample holders with axial symmetry". J. Non-Newtonian Fluid Mech., Vol.97, pp.1-12.
- Ram, A., Finkelstein, E., Elata C., 1967, "Reduction of friction in oil pipelines by polymer additives", I & EC Process Design and Development, Vol.6, pp. 309-313.
- Sellin, R. H. J., Hoyt J. W., Scrivener O., 1982, "The effect of drag-reducing addditives on fluid flows and their industrial applications – Part 1: Basic Aspects", J. Hydraul. Res., Vol.20, pp. 29-82.
- Virk, P. S., Merrill E. W., Smith K. A., 1967, "The Toms phenomenon: turbulent pipe flow of dilute polymer solutions", J. Fluid Mech., Vol.30, pp. 305-328.
- Wilkes, J. O., 1999, "Fluid Mechanics for Chemical Engineers", Ed. Prentice-Hall PTR, New Jersey.
- Wilkens, R. J., Thomas, D. K., 2007, "Multiphase drag reduction: Effect of eliminating slugs", International Journal of Multiphase Flow, Vol.33, pp.134-146.
- Zhang, Y., Schmidt, J., Talmon, Y., Zakin, J. L., 2005, "Co-solvent effects on drag reduction, rheological properties and micelle microstructures of cationic surfactants", J. Colloid Interf. Sci., Vol.286, pp.696-709.

### 7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.