Comparative study of the effects caused by polymers, bubbles and surfactants in a turbulent flow

Estudio comparativo de los efectos causados por polímeros, burbujas y tensioactivos en un flujo turbulento

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Abstract

In the present work, the particle image velocimetry (PIV) technique was used to measure the velocity components in the direction normal and tangent to the wall to obtain average velocity fields, wall shear stresses, friction velocity, drag reduction and average deformation fields were obtained by adding bubbles (injected by electrolysis), polymer (WSR-301 polyox) and surfactant (cationic) and their bubble-polymer, bubble-surfactant and polymer-surfactant combinations at concentrations of 164 and 272 ppm in a water flow in a channel (2cm x 10cm x 160cm) with a Reynolds number of 5200. Increased levels of drag reduction were obtained when combining the techniques, for example in the bubbles with polymers (WSR - 301 polyox) combinations, drag reduction results of 82 and 93 % were obtained for the concentrations of 164 and 272 ppm respectively, While when the combinations of bubbles with surfactants were used, the results were 37 % for 164 ppm and only 16 % for 272 ppm, and for the combination of polymer with surfactant for 164 ppm the results were 47 % and for 272 ppm the drag increased by 25 %, possibly due to an incorrect preparation of the polymer or surfactant, which leads to the conclusion that the greatest synergistic benefit is presented when combining the drag reducing techniques of bubbles and polymers.

Bubbles, Polymers, Surfactant

Resumen

En el presente trabajo se usó la técnica de velocimetría de imagen de partículas (PIV) para medir las componentes de velocidad en dirección normal y tangente a la pared con lo que se obtuvieron campos de velocidad promedio, esfuerzos de corte en la pared, velocidad de fricción, reducción del arrastre y campos de deformación promedio adicionando burbujas (inyectadas por electrolisis), polímero (polyox WSR-301) y surfactante (catiónico) y sus combinaciones burbujas-polímeros, burbujas-surfactanes y polimeros-surfactantes en concentraciones de 164 y 272 ppm en un flujo de agua en un canal (2cm x 10cm x 160cm) con un número de Reynolds de 5200. Se obtuvieron incrementos en los niveles de reducción del arrastre al combinar las técnicas, por ejemplo en las combinaciones burbujas con polímeros (polyox WSR - 301) se tuvieron resultados en la reducción del arrastre del 82 y 93 % para la concentraciones de 164 y 272 ppm respectivamente, mientras que cuando se utilizaron las combinaciones de burbujas con surfactantes se tuvo 37 % para 164 ppm y apenas 16 % para 272 ppm y para la combinación polímero con surfactante para 164 ppm se tuvo 47 % y para 272 ppm el arrastre aumentó en 25 % posiblemente debido a una incorrecta preparación del polímero o del surfactante, por lo que se llega a la conclusión de que el mayor beneficio sinérgico se presenta al combinar las técnicas reductores del arrastre de burbujas y polímeros.

Burbujas, Polímeros, Surfactanes

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Introduction

The production and the way in which energy is used generate an environmental impact at all scales, threatening future development. The abundance of energy as well as the lack of awareness about the impact of its use on the environment have facilitated, on the one hand, human, commercial and industrial activities of intensive and inefficient energy consumption and, on the other hand, the disorderly growth of cities, which today are real machines of energy consumption as well as producing huge amounts of waste that are devouring the natural environment.

Therefore a large number of systems are designed to transport a fluid from one place to another with a specified expense, speed and elevation difference, during this process the system can generate mechanical work in a turbine or it can consume this type of work in a pump or a fan (M. A. Asidin, E. Suali, T. Josnukin, F. A. Lahin, 2019).

For these reasons the phenomenon of drag reduction in pipelines has received much attention for decades due to its potential applications in engineering, especially in the fluid transport industry. Various methods to improve drag reduction have been developing over the past few years and are divided into 2 categories mainly; additive methods and non-additive methods. Drag reduction using a polymer as an additive is one of the most attractive and studied methods. Reducing drag in pipelines means using less pump power to move a fluid thus offering economic savings for companies (White F. , 2008). Recent research on improving heat transfer in pipe flow shows that thermal performance is generally accompanied by an increase in pressure drop.

To solve this problem the development of drag reduction technology is very promising and researches on this topic have attracted more and more attention (Weichi Gang, Jun Shen, Wei Dai, Ke Li, Maoqiong Gang, 2021). That is why the implementation of drag reduction technologies to the various means of transport or pumping systems, represent savings of billions of dollars annually, and thus, being that the issue of turbulent drag reduction is not new, it has resumed a new worldwide boom due to the large amount of money that could be saved.

Drag reduction was defined as a reduction in the pressure drop of a turbulent flow in a pipe due to the addition of a drag reducer (bubbles, polymers, surfactants, etc.) as they cause a reduction of the shear stress in the wall τ_{wall} or the coefficient of friction.

One definition of drag reduction is:

"Drag reduction is the decrease in the coefficient of friction of the mixture of the drag reductant with the solvent (substance that allows the dispersion of another substance in this at the molecular or ionic level) in a turbulent flow below the coefficient of the solvent (water for this experiment)" (Lumley, 1969).

This implies that the flow of the solution has to be turbulent, and that the coefficient of friction is less than that of Newtonian flow, provided that the mixture and the solvent are considered to have the same viscosity.

On the other hand, it has been seen that drag-reducing solutions are generally non-Newtonian, so that the viscosity of the drag-reducing solutions is less than that of Newtonian flow. Newtonian so that the viscosity is no longer a constant and this can be one of the main problems in describing the drag reduction phenomenon. Around this definition it is important to define the ratio of the friction factor or the shear stress ratio (τ_{wall}), for the solution with the subscript S and the Newtonian solvent with the subscript N:

$$C_\tau = \frac{\tau_{\text{wall}S}}{\tau_{\text{wall}N}} \tag{1}$$

The shear stress in the wall and the coefficient of friction are related by:

$$f = \frac{\tau_{\text{wall}}}{\frac{\rho}{2}\bar{u}^2} \tag{2}$$

Where $\bar{u}$ is the average velocity given by.

$$\bar{u} = \frac{Q}{A} \tag{3}$$

With Q being the flow rate and A being the cross-sectional area of the pipe. Therefore, it can also be written as:

$$Cf = \frac{f_s}{f_N} \tag{4}$$

The most common, however, for reporting drag reduction is by percentage.

$$DR = 1 - \frac{f_s}{f_N} \quad \text{o} \quad 1 - \frac{\Delta P_s}{\Delta P_N} \qquad (5)$$

The phenomenon of drag reduction was first observed in 1948, where a reduction of over 50% was achieved with only 250 ppm of polymethyl methacrylate solution, which caused the interest of many researchers in the addition of polymers and surfactants in pipes and channels (Toms, 1948).

The addition of polymers to a turbulent flow causes a dramatic reduction in Reynolds stresses (Re) and in fluctuating velocities perpendicular to the flow direction (v'). Numerous works on drag reduction by adding polymers have been carried out in recent decades; a brief review of investigations on drag reduction by adding external agents follows.

The changes in turbulent structures are very important that is why a number of important parameters such as molecular weight, flexibility, length and expansion are mentioned, because the polymer molecules during the drag reduction phenomenon are stretched in the turbulent boundary layer resulting in an increase in the viscosity of the fluid (A.Gyr, H.W. Bewersdorff, 1995).

A study conducted in 2010 where a small amount of CTAC NaSal (75 ppm) was added and studied by pressure drop using a particle image velocimetry system where a drag reduction of 75% was achieved. As conclusions it was observed, firstly, that the pressure drop depends on the fluid velocity, secondly, the results obtained in the PIV show that the amount of concentrated surfactant solution is strongly affected. While in a fully turbulent flow the kinetic energy of the solution is small and the Reynolds stress negligible (Ferhat Hadri, Sylvain Guillou, 2010).

Although the drag reduction increases with increasing polymer concentration, an asymptote is reached where the addition of polymer is no longer beneficial. With the right choice of parameters, polymers can reduce drag beyond the limiting asymptote, eliminating turbulence and giving way to laminar flow. At large concentrations the laminar state becomes unstable, resulting in fluctuations.

The results indicate that the asymptotic state is directly disconnected from the obtained turbulence (George H. Choueiri, José M López, Björn Hof, 2018).

Another experimentation performed in 2018 used a solution of a cationic surfactant, Cetyl Methyl Ammonium Chloride and a nonionic polymer. Six different solutions with different concentrations were made at different temperatures from 25°C to 50°C. It was found that the mixed solution curves could be divided into; Enhanced Drag Reduction Zones, Stable Drag Reduction Zones and Destroyed Drag Reduction Zone. The addition of polymers also increased the drag reduction efficiency in the destroyed zone by providing a wider Reynolds number range. In addition, the results indicated that temperatures influenced more than concentrations, so raising the temperature to change the solution structure is more effective than increasing the amount of structures (Dongjie Liuun, Qinghui Wang unJinjia Wei, 2018).

An important problem of drag reduction in turbulent flow with polymers is the diameter effect. A new method was developed in which the Reynolds number along with the friction factor is transformed into the Prandtl-Von Karman number.

Where these new parameters are correlated in straight lines.

It was found that the slope and intersection of these straight lines can be predicted by empirical correlations involving diameter and polymer concentrations. Thus if *Re* and *f* of the flow of a small diameter pipe are known, these two correlations can predict the characteristics for large pipe diameters.

With this method most of the relative errors between predicted data and experimental data are within 20%, much better than the traditional scale (Xin Zhan, Xiaodong Dai, Jishi Zhao, Dengwei Jing, Fei Liu, Lei Li, Yanping Xin, Kun Liu., 2021).

Another research conducted in 2021 experimentally compared in a turbulent flow with three different additives; a flexible polymer, a rigid polymer and a surfactant.

A high drag reduction of approximately 58% was achieved using the flexible polymer and a maximum drag reduction of 70% was achieved with the flexible polymer and surfactant. The flexible polymer and surfactant solution had a small shear viscosity, on the other hand, the rigid polymer solution had a large shear viscosity with considerable shear thinning. In addition the flexible polymer solution was the only one that exhibited a large extensional relaxation time during the experiment (Lucas Warwaruk, Sina Ghaemi, 2021).

While, in 2022, the feasibility of applying a cationic surfactant as a reducing agent was sought through rheological test and simulations. The results of the experiment showed that the surfactant, Cetyl Methyl Ammonium Chloride, has excellent thixotropy and the viscosity recovery rate for 300 seconds can reach 97%. In addition, the CTAC/NaSal (Sodium Silicate) solution has a high oil resistance and salt tolerance. If the oil concentration increases from 0 to 6000 ppm the viscosity only decreases by 8.24% if the salt concentration increases from 0 to 6000 ppm the maximum viscosity reached will be 87.08%. It should be noted that the CTAC/NaSal solution has good temperature resistance (Ying Yuan; Jiaqiang Jing; Ran Yin; Peiyu Jing; Jianfei Hu, 2022).

A study conducted with Al_2O_3 nanoparticles with concetrations of 100 ppm, 200 ppm and 300 ppm with a mixing duration of 30, 60 and 120 min respectively, with a circular pipe used as a comparison of a spiral pipe, the two pipes mounted horizontally. The results yielded that with Reynolds number between 4,000 and 20,000 show a high drag reduction of 38% in the spiral pipe (Yanuar, Sealtial Mau, Kurniawan T. Waskito, Okky A. Putra,Rifqi Hanif, 2017).

In a more recent study it was found that the addition of SiO_2 nanoparticles to the cationic polyamide(PAM) solution quite efficient in reducing drag, but only at higher flow velocities with Reynolds number above 6000. While at lower Reynolds no improvement is perceived. The addition of SiO_2 to the PAM solution plays a dual role. The first is an increase in flow resistance caused by Brownian motion of the particles, the second is a decrease in flow resistance caused by acting as nodes to protect the polymer chain from induced stress.

At an optimal concentration of nanoparticles and high Reynolds numbers, the latter effect is dominant, resulting in higher drag reduction performance (Xiaoping Li, Jiaxin Pan 1Jinwen Shi, Yanlin Chai, Songwei Hu, Qiaorong Han, Yanming Zhang, Xianwen Li, Dengwei Jing, 2023).

After having made a literature review over the last 70 years of both experimental and numerical studies that have been carried out on drag reduction by adding bubbles, polymers, surfactants independently and their combinations, it can be concluded that there are many investigations of drag reduction by adding bubbles by different methods, adding polymers either by injection or by creating a homogeneous solution with the solvent and adding surfactants.

However there are very few studies combining two of the above techniques, for that reason it was decided to carry out this study, where a turbulent flow of water in a channel (2 cm wide x 10 cm high x 160 cm long) was analyzed experimentally, adding first bubbles, polymers and surfactants for the concentrations of 164 and 272 ppm independently and then adding the combinations of bubbles with polymers, bubbles with surfactants and polymers with surfactants also for the concentrations of 164 and 272 ppm, The drag reduction obtained by combining two techniques was greater than that obtained with a single technique; on the other hand, the greatest drag reduction was obtained with the combination of polymer with bubble for 272 ppm, also shown were the average velocity fields (in units of the international system and in units of the wall) and the average deformation maps (dimensionless) for the different working conditions, as well as the values of the shear stress in the wall, the friction velocity and a study of the average deformation in the damping sublayer (y+ = 7 = 0. 48mm) for the critical conditions water with polymer and water with bubbles - polymer both for 272 ppm compared to the solvent without drag reducing additives, which justified the drag reduction values obtained for those conditions.

Experimental setup

The technique that was used to carry out the experimentation is particle image velocimetry (PIV), which is a technique used to obtain instantaneous velocity fields.

The camera used in this experiment is Megaplus ES 1.0, which can capture 30 images per second, with a resolution of 1008 x 1018 pixels. The laser used is an Nd:YAG, which produces through an optical array a sheet of light with a length of 532 nm (green color) and an energy per pulse of 32 mJ (see Figure 1).

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Figure 1 Photograph of the experimental setup

Figure 2 shows the channel with dimensions (2cm x 10cm x 160cm), where the experimental tests were performed and through which water was passed with an inlet flow of 15 lpm and using the hydraulic diameter ($D_{Hydraulic}$) the average velocity was calculated with equation 3 and substituting in equation [6] the Reynolds number (Re) is obtained.

$$Re = \frac{\rho X \bar{u} X D_{Hydraulic}}{\mu} = 5200 \qquad (6)$$

Figure 2 also shows test zone 3, where the flow is fully developed and therefore the velocity measurements were carried out there. On the other hand, test zone 1 is also shown, in which it was calculated that 66 pix correspond to 1 mm and the time between photographs ($t_{adjustment}$) is calculated by means of equation 7.

$$tadjustment = 1x10^6 \, x \frac{0.25 \, x \, I_{AI}}{f_{px} \, x \, \bar{u}} \qquad (7)$$

Where: I_{AI} is the size of the interrogation area, f_{px} is the equivalent of a pixel in millimeters, $\bar{u}$ is the average flow velocity and 0.25 is the minimum distance that a particle of the interrogation area must travel.
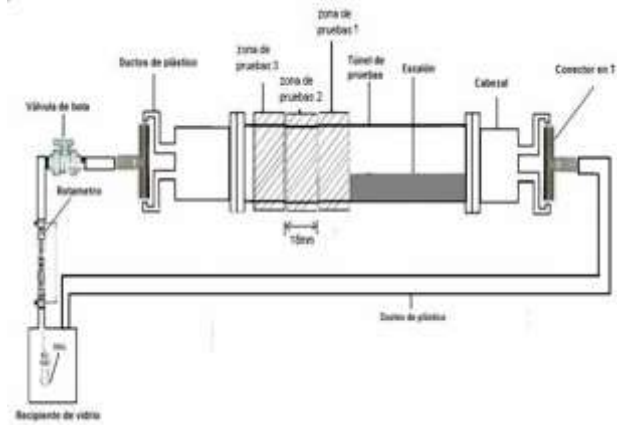
It is substituted into equation 7.

Figure 2 Experimental setup

In this way it was determined that the time between photographs should be 1100µs. A photograph of test area 3 can be seen in Figure 4.
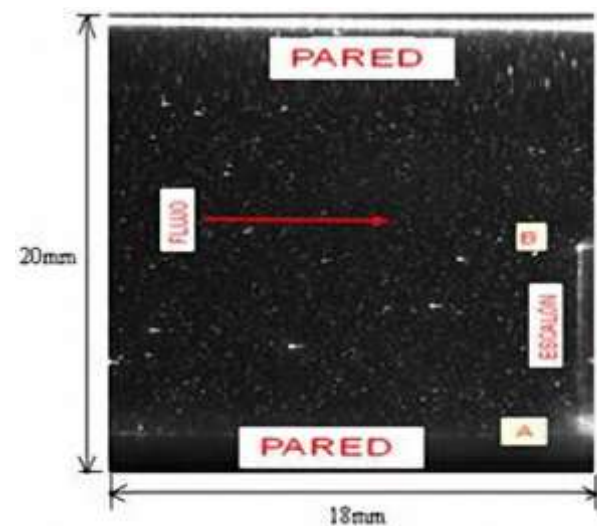

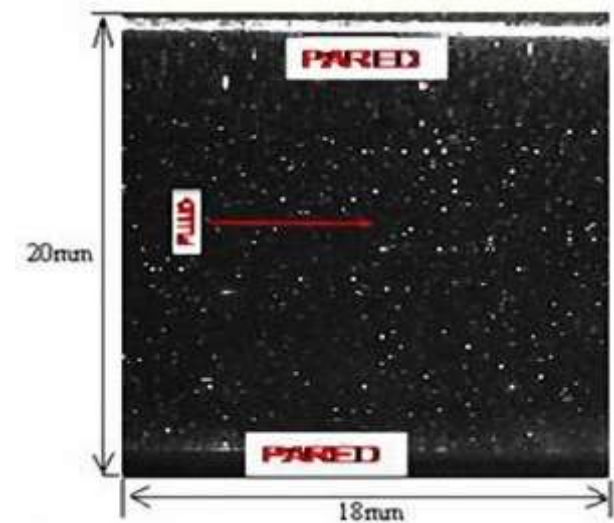
Figure 3 Experimental setup

Figure 4 Experimental setup

Figure 5 shows the test matrix in which it is indicated that first we worked with water (without external agents), then we added bubbles (d = 10µm), cationic surfactant (sulfate-free shampoo) and polymers in concentrations of 164 and 272 ppm independently and finally we made the combinations of bubbles with polymers, bubbles with surfactants and polymers with surfactants also for the concentrations of 164 and 272 ppm.
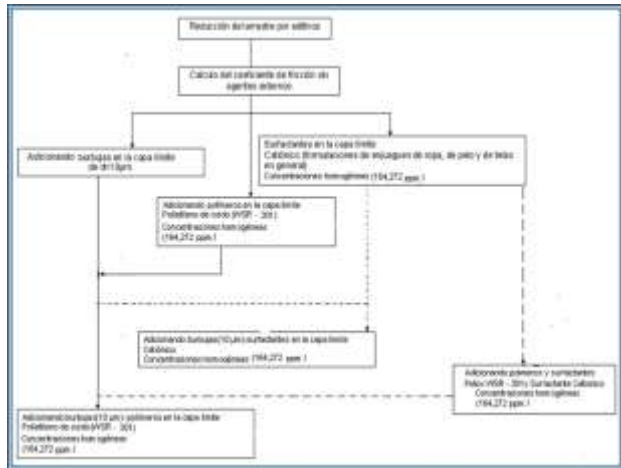

Figure 5 Test Matrix

On the other hand, the bubbles were produced by electrolysis and the electrical conductor was a thin copper wire of 10 µm diameter, fed by a voltage source of 20 Volts direct current. The power supplied to the circuit was set to a maximum value of 0.354W, to avoid significant corrosion effects on the cathode.

The average diameter of the hydrogen bubbles obtained was approximately 10µm. Figure 6 shows a velocity contour, which was modeled with the Fluent version 5.6 computational software, where it can be seen that at approximately 130 diameters (16cm) of the wire in the direction of the free current, the velocity gradients are no longer affected by it (Alejandro Alonzo Garcia, 2009). This allowed us to conclude that by placing the wires at 20cm from the test area, the disturbances induced by their presence will be significantly minimized.
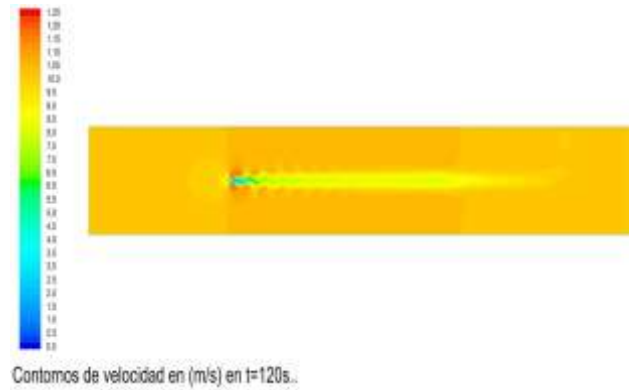

Contornos de velocidad en (m/s) en t=120s..

Figure 6 Contour Map [15]

Table [1] shows the experimental matrix in the first column shows the number of Re, in the second column shows the working conditions for 1 phase, which refers to the solvent (water) without drag reducing additives, 2 phases is when a drag reducing agent is added and three phases means that the mixtures bubbles with polymer, bubbles with surfactant and polymer with surfactant are added, on the other hand in column 3 is the electrical power consumed by the wire and in the last column the vacuum fraction.

Reynolds	Tests	Electrical power (W)	α (%)
5200	1 Phase	0	0
	2 Phases	0.782	0.782
	3 Phases	0.782	0.782

Table 1 Experimental matrix for bubles

$$\alpha = \frac{A_{burbujas}}{A_t} \qquad (8)$$

The void fraction was calculated with equation 8 and in Figure 7 a photograph is shown, in which it can be seen that the bubbles and the tracer seeds give off a certain amount of light, when they pass through the PIV laser, then an application developed in Visual C++ software was used (the software was developed by A. Alonzo Garcia (Alejandro Alonzo Garcia, 2009)) was used to transform the light given off into an average grayscale value, which are 198 for the seeds and 255 for the bubbles and in this way the number of bubbles that were injected can be estimated and because the diameter of the bubbles is known the area occupied by the bubbles can also be calculated.
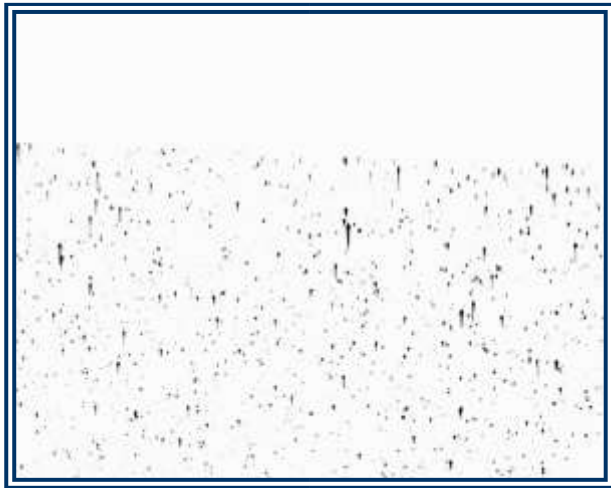
Figure 7 Bubbles obtained from the filtration process

Experimental results of properties of the mixtures of water with polymer and water with its surfactant

There is a possibility that the addition of polymers and surfactants in the working fluid (water) may alter the viscosity and density, for this reason it was decided to perform experimental measurements of water-polymer and water-surfactant solutions with a pycnometer (5 ml) and a viscometer.

Table 2 shows the values of density and absolute and kinematic viscosities of the polymer-water solution mixed by hand with water replacement (the solvent is replaced for each working condition) and Table 3 without water replacement (the solvent is not replaced for each working condition), while Table 4 shows the values with water replacement but mixing the solution with a blender and Table 5 also uses a blender but without water replacement.

PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.040	0.955	0.918
500	1.010	0.958	0.949
800	1.008	0.981	0.973
1000	1.024	1.002	0.979
1500	1.002	1.012	1.010
2000	1.030	1.02	0.990

Table 2 Property values of the hand-mixed polymer-water solution with water replacement for different concentrations

PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.008	0.956	0.948
500	1.011	0.957	0.947
800	1.012	1.006	0.994
1000	1.002	0.979	0.977
1500	1.008	1.065	1.057
2000	1.014	1.03	1.016

Table 3 Property values of the polymer-water solution mixed by hand without water replacement for different concentrations.
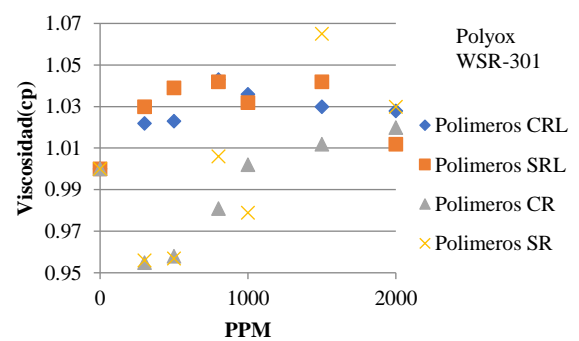
PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.007	1.022	1.015
500	1.005	1.023	1.018
800	1.012	1.043	1.031
1000	1.013	1.036	1.023
1500	1.016	1.03	1.014
2000	1.009	1.009	1.000

Table 4 Property values of the polymer-water solution mixed in a blender with water replacement for different concentrations
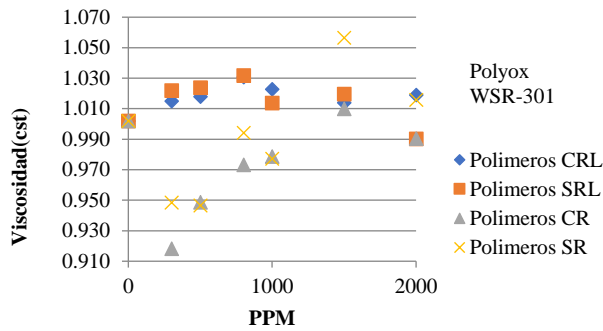
PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.008	1.030	1.022
500	1.015	1.039	1.024
800	1.010	1.042	1.032
1000	1.018	1.032	1.014
1500	1.022	1.022	1.000
2000	1.022	1.012	0.990

Table 5 Property values of the mixed polymer-water solution in blender without water replacement for different concentrations

Graph 1 shows the behavior of the absolute viscosity of the polymer-water solution with respect to the concentration in parts per million (ppm) of the additive for each condition, Graph 2 shows the kinematic viscosity and Graph 3 shows the density.

Graph 1 Absolute viscosity values of the polymer-water solution for different concentrations

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Graph 2 Values of the kinematic viscosity of the water-polymer solution for different concentrations.
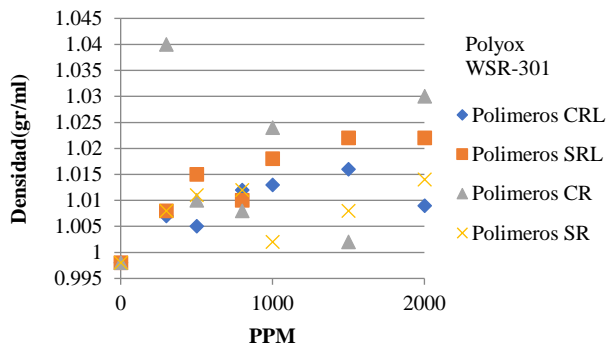
Graph 3 Values of the density of the water-polymer solution for different concentrations.

Graph 1 shows that the absolute viscosity of the water-polymer solution varies between 0.2% (where the solution is mixed by hand with water replacement and a concentration of 1000ppm) to 4.2% (where the solution is mixed in a blender without water replacement and for concentrations of 800 and 1500 ppm).

On the other hand, Graph 2 shows that the kinematic viscosity of the waterpolymer solution varies from 0.6% (where the solution is mixed by hand without water replacement and for a concentration of 800ppm) to 5% (where the solution is mixed by hand with water replacement and for a concentration of 500 ppm).

Finally, Graph 3 illustrates that the density of the water-polymer solution varies from 0.2% (where the solution is mixed by hand without water replacement and for a concentration of 1000ppm) to 4% (where the solution is mixed by hand with water replacement and for a concentration of 300 ppm).

Based on the above it can be said that the extreme lower and upper values of the properties (density and viscosities) of the water-polymer solution are given when it is mixed by hand and the most homogeneous values are given when it is mixed in a blender.

Table 6 shows the values of density and absolute and kinematic viscosities of the surfactant-water solution mixed by hand with water replacement and Table 7 without water replacement, while Table 8 shows the values with water replacement but mixing the solution with a blender and Table 9 also uses a blender but without water replacement.

PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.014	1.045	1.031
500	1.002	1.038	1.036
800	1.01	1.048	1.038
1000	1.01	1.026	1.016
1500	1.022	1.016	0.994
2000	1.018	1.016	0.998

Table 6 Property values of the surfactant-water solution mixed by hand with water replacement for different concentrations.

PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.001	1.02	1.019
500	0.995	1.026	1.031
800	0.995	1.027	1.032
1000	0.986	1.04	1.055
1500	0.98	1.026	1.047
2000	0.998	1.026	1.028

Table 7 Property values of the surfactant-water solution mixed by hand without water replacement for different concentrations

PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.011	1.045	1.034
500	1.006	1.040	1.034
800	1.007	1.007	1.000
1000	1.016	1.040	1.024
1500	0.991	1.043	1.052
2000	1.018	1.037	1.019

Table 8 Property values of the surfactant-water solution mixed in Blender with water replacement for different concentrations

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PPM	Density (g/ml)	Dynamic Viscosity (cp)	Viscosity Kinematic (cst)
0	0.998	1	1.002
300	1.024	1.032	1.008
500	1.021	1.011	0.990
800	1.02	0.995	0.975
1000	1.016	0.988	0.972
1500	1.017	1.031	1.014
2000	1.018	1.029	1.011

Table 9 Property values of the surfactant-water solution mixed in blender without water replacement for different concentrations.
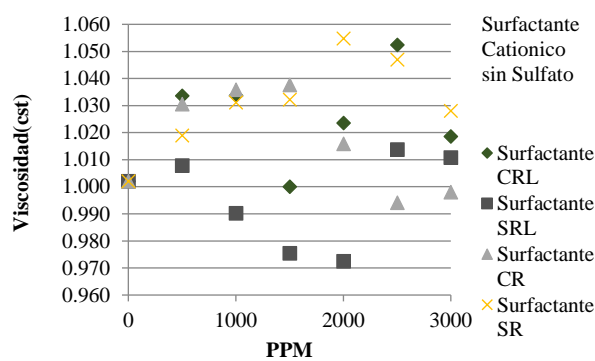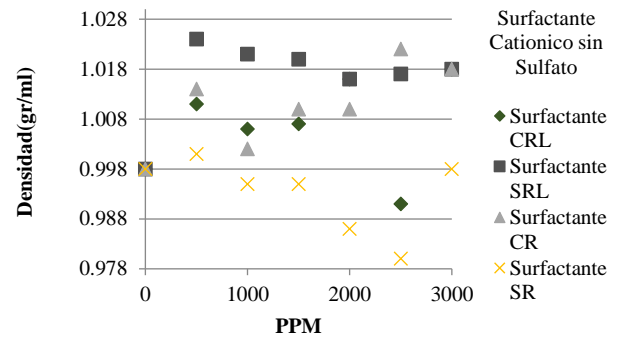
Graph 4 shows the behavior of the absolute viscosity of the surfactant-water solution with respect to the concentration in parts per million (ppm) of the additive for each condition, Graph 5 shows the kinematic viscosity and Graph 6 shows the density.
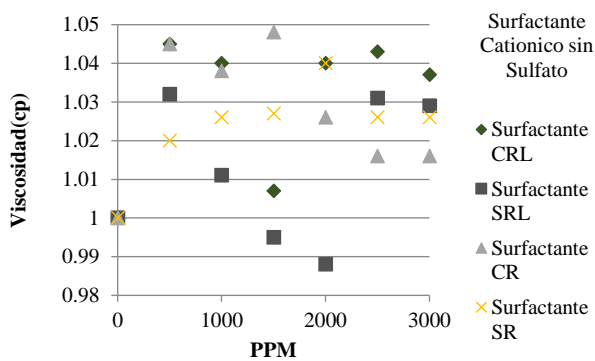
Graph 4 Values of the absolute viscosity of the water-surfactant solution for different concentrations.

Graph 5 Values of the kinematic viscosity of the water-surfactant solution for different concentrations.

Graph 6 Values of the density of the water-surfactant solution for different concentrations

Graph 4 shows that the absolute viscosity of the water-surfactant solution varies from 0.5% (where the solution is mixed in a blender without water replacement and for a concentration of 1500 ppm) to 4.8% (where the solution is mixed by hand with water replacement and for a concentration of 1500 ppm).

On the other hand, Graph 5 shows that the kinematic viscosity of the water-surfactant solution varies from 0% (where the solution is mixed in a blender with water replacement and a concentration of 1500ppm) to 5% (where the solution is mixed by hand with water replacement and for a concentration of 2500 ppm).

Finally, Graph 6 illustrates that the density of the water-surfactant solution varies from 0.1% (where the solution is mixed by hand without water replacement and for a concentration of 500ppm) to 2.4% (where the solution is mixed in a blender without water replacement and for a concentration of 500ppm).

Based on the above it can be said that the lower and upper extreme values of the properties (density and viscosities) of the water-surfactant solution is not affected by the mixing method and is also not affected by the water replacement and for that reason it was decided to work in this experiment by mixing the polymers and surfactants without water replacement and blending them but the most important thing was that the densities and viscosities of the water-polymer and water-surfactant solutions are not affected by the mixing method and also not affected by the water replacement. polymer and water-surfactane solutions vary by less than 5% for all conditions with respect to water so the density and viscosity of water can be used in the data obtained.

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Experimental results for turbulent water flow with the addition of bubbles, polymer and surfactants

The average velocity profiles in International System units and in wall units, as well as the drag reduction and average deformation fields (dimensioned by multiplying by the hydraulic diameter DHydraulic and dividing by the local average velocity $\bar{u}$) in a turbulent water flow for a Re = 5200 with the addition of bubbles were determined, cationic surfactant (sulfate-free shampoo), polymers (polyox WSR301) and their combinations bubbles with polymers, bubbles with surfactants and polymers with surfactants for concentrations 164 and 272 ppm, in the horizontal center plane of test zone 3 of the channel.

The average velocity field presented in Figure 8 is averaged only with respect to time and in Figure 9 a small section (4 x 4 mm) of this same velocity field is presented so that the velocity vectors can be better appreciated and in Graph 7 it is shown averaged not only with respect to time but also with respect to space resulting in average velocity profiles in the fully developed flow region (test zone 3, which was tested with $\frac{du}{dx}$ ~0) temporally and spatially averaged for each work condition.
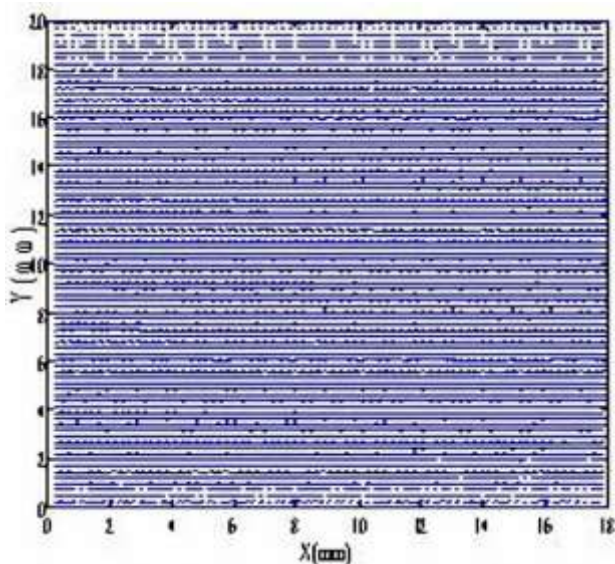

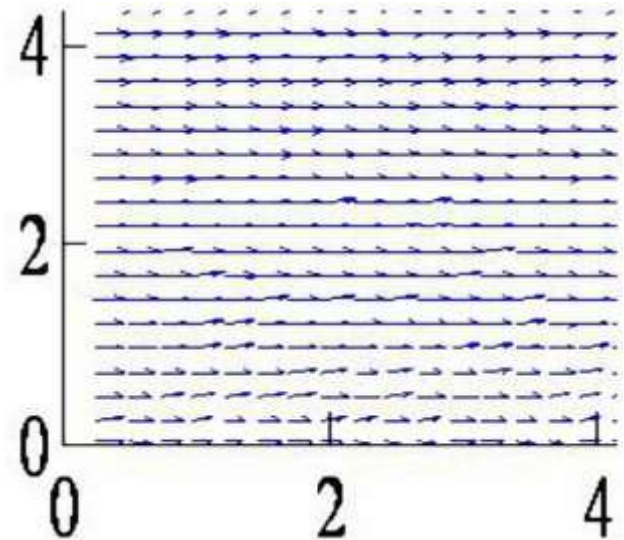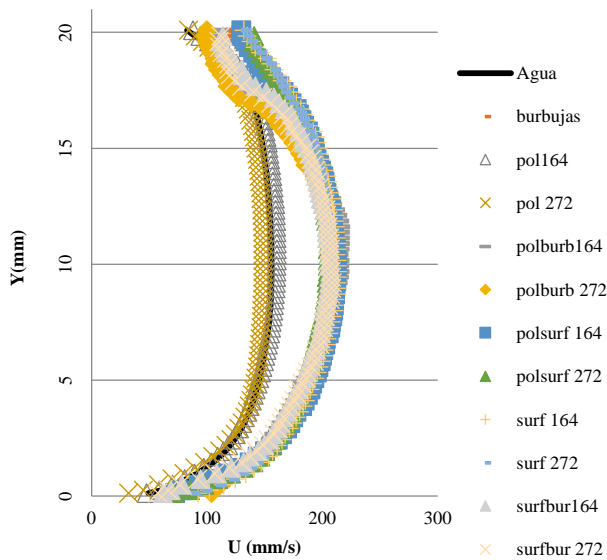**Figure 8** Averaging velocity field test zone 3

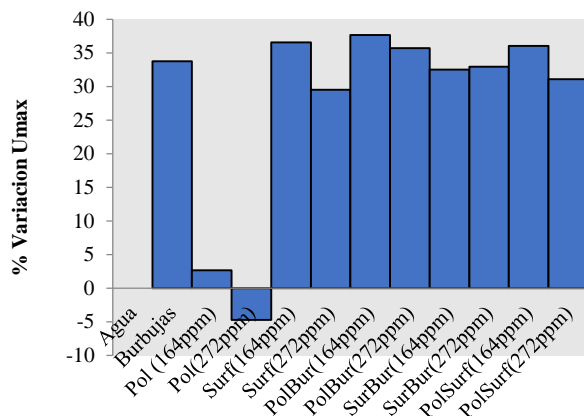**Figure 9** Trimmed average speed field test zone 3

It is evident that the velocity increases or decreases depending on the working condition. Taking as a parameter the velocity in the center of the channel, which is the maximum velocity (umax) that can be reached. Then, when working only with surfactants the umax increased 36.55 and 29.48 % for the concentrations of 164 and 272 ppm respectively, while when polymers were added the umax behaved differently, increasing 2.65% for 164 ppm and decreasing 4.73% for 272 ppm.

In the case of the bubbles there was an increase of 33.76% and in the combination of surfactant (sulfate-free shampoo) with bubbles there were considerable increases of 32.48 and 32.93% for 164 and 272 ppm respectively, on the other hand in the combinations of bubbles with polymers there were increases of 37.64 and 35.67% for the same concentrations.

Finally, for the combinations of polymer with surfactant, there were increases of 36.01 and 31.07 % also for 164 and 272 ppm as shown in Figure 8.

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Graph 7 Average velocity profiles in the fully developed flow zone (test zone 3).

Graph 8 Variation of umax for each working condition.

The wall shear stresses and friction velocity were also calculated using the first order forward finite difference method for each working condition, then substituting the values obtained from the velocity profiles in Eqs. [9] and [10].

$$\tau wall \ = \mu \frac{du}{dy} \tag{9}$$

Where μ is the absolute viscosity of water (1cp), du/dy is the velocity gradient with respect to the distance from the wall.

$$u\tau = \sqrt{\frac{\tau_{wall}}{\rho}} \tag{10}$$

Where ρ is the density of the solvent (water).

Substituting in equation [11] the shear stress of the water wall with and without additives, the drag reduction percentages are obtained.

$$DR\% = \frac{\left|\tau_{water} - \tau_{additive}\right|}{\tau_{water}} X100 \tag{11}$$

Table 10 shows the values of shear stresses, friction velocities and drag reduction percentages for each condition. In which a drag reduction of 69.12% is shown for bubbles, for surfactants (sulfate-free shampoo) drag reductions were obtained for 164 and 272 ppm of 11.47 and 7.58% respectively, however for the case where polymers were added (Polyox WSR-301) there was only a reduction of 0.05% for 164 ppm, so it can be considered that there was no change in drag for that working condition and for 272 ppm there was an increase in drag of 15%, and in the case where polymers were added (Polyox WSR-301) there was only a reduction of 0.05% for 164 ppm, so it can be considered that there was no change in drag for that working condition, and for 272 ppm there was an increase in drag of 15%.

In the case where two techniques were combined, the greatest drag reductions for bubbles with surfactant were 37.36 and 16.16 % for 164 and 272 ppm, while for surfactants with polymers a drag reduction of 46.98 % was obtained for 164 ppm and an increase of 24.9% for 272 ppm, the best results in drag reduction were obtained with the combination of bubbles with polymers, which were 82.01 and 93.1 % also for 164 and 272 ppm. This is illustrated in Figure 9.

However, it is always important to dimension in order to compare the results, which was done by substituting the values of velocity and distance with respect to the wall in equations [12] and [13].

$$u^+ = \frac{u}{u_\tau} \tag{12}$$

$$y^+ = \frac{yu_\tau}{v} \tag{13}$$

	τ (N/m^2)	$u\tau$ (m/s)	DR (%)
Water	0.0914	0.0096	-
Bubbles	0.0282	0.0053	69.12
Surfactant(164PPM)	0.0809	0.0089	11.47
Surfactant(272PPM)	0.0845	0.0092	7.58
PolymeR (164PPM)	0.0913	0.00956	0.052
Polymer (272PPM)	0.1053	0.01026	-15.1
Surfburb(164PPM)	0.0573	0.0075	37.36
Surfburb(272PPM)	0.0766	0.0087	16.16
Surfburb(164PPM)	0.0164	0.0040	**82.01**
Polburb(272PPM)	0.0063	0.0025	**93.10**
Polsurf(164PPM)	0.0485	0.0069	46.98
Polsurf(272PPM)	0.1142	0.0107	-24.9

Table 10 Values of shear stress, friction velocity and drag reduction for bubbles and surfactants
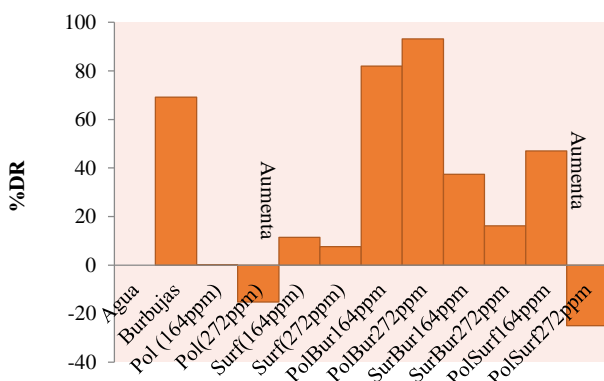
Graph 9 Variation of drag reduction in percentages for each working condition

Graph 10 shows the profiles in wall units, the profiles below the water profile indicate that the drag increases and above that it decreases.
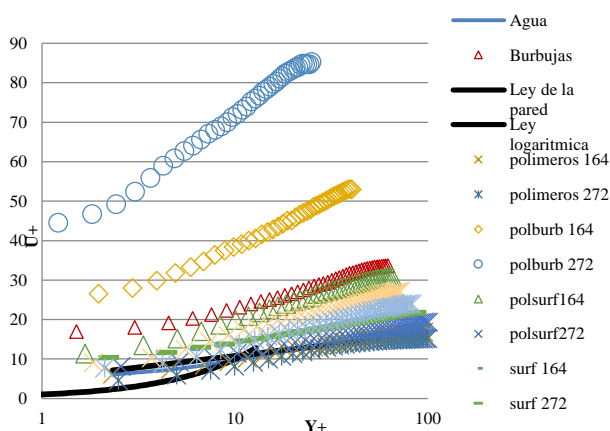
Graph 10 Velocity profiles in wall units

However, something that strongly calls the attention is what happened with the average deformation. In Figure [10], the average deformation field (dimensionless by multiplying by DHydraulic and dividing by $\bar{u}$) is illustrated for the condition without drag reducing agents and in the conditions where bubbles were independently added, cationic surfactant (sulfate-free shampoo) and polymers for 164 and 272 ppm.

Where it is seen that the average strain increases considerably from 2 to 3 times its value, while in the conditions where only polymers (polyox WSR-301) were added there is no considerable change in the average strain.

Figure 11 shows the deformation fields for the conditions where the combinations of bubbles with surfactants, bubbles with polymers and surfactants with polymers were added for the concentrations of 164 and 272 ppm, the deformation increased from 2 to 4 times its value. On the other hand, in the zone close to the wall, the deformation does not behave in the same way, unfortunately in the experiment presented it was not possible to visualize the viscous sublayer (y+ < 5), which is the zone closest to the wall, but according to Graph 10, the damping sublayer (5<y+ < 30) was visible.

Figure 12 shows the deformation field in both smooth curves and pixels (giving a matrix of 73 columns) in the near-wall zone (y < 2 mm) of the water without drag-reducing additives compared to the critical condition.

Where polymer was added for a concentration 272 ppm having a 15% increase in drag and Figure 13 also shows the comparison of water deformation in the same zone (and < 2 mm) with the condition, where bubbles were added with polymer for 272 ppm having a drag reduction of 93. 1%. These two critical conditions are supported by the values in Tables 11 and 12. Table 11 shows the strain values for the conditions where only polymer was added for 272 ppm, the values for water without additives and the difference of both conditions in the damping sublayer (y+ = 7 = 0. 484mm), which helps to know if the deformation increased or decreased with the drag reducing agent, if the difference gives us positive the drag decreases and if it gives us negative the drag increases, in this case the deformation values are shown in the row corresponding to y+ = 7 = 0.484mm (damping sublayer) and for the range from column 23 to 32, because in those points it is very well appreciated how the deformation increases and therefore that causes the drag to increase by 15%.

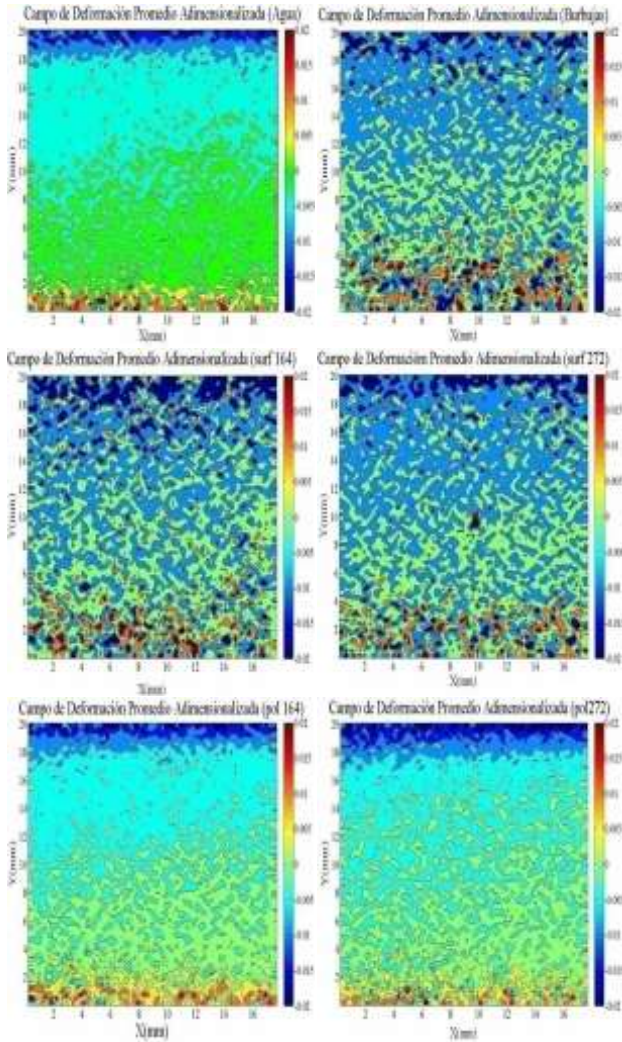LÓPEZ AGUADO-MONTES, José Luis, RIVERA-LÓPEZ, Jesús Eduardo, ARCINIEGA-MARTÍNEZ, José Luis and JUAREZ-NAVARRO, Carlos Alfonso. Comparative study of the effects caused by polymers, bubbles and surfactants in a turbulent flow. ECORFAN Journal-Taiwan. 2023

Figura 10 Campos de deformación para agua, surfactantes y polímeros para 164 y 272ppm.
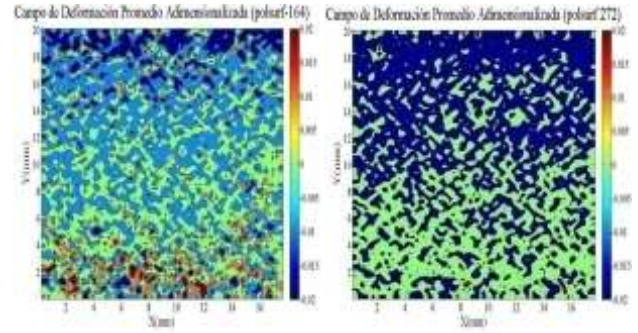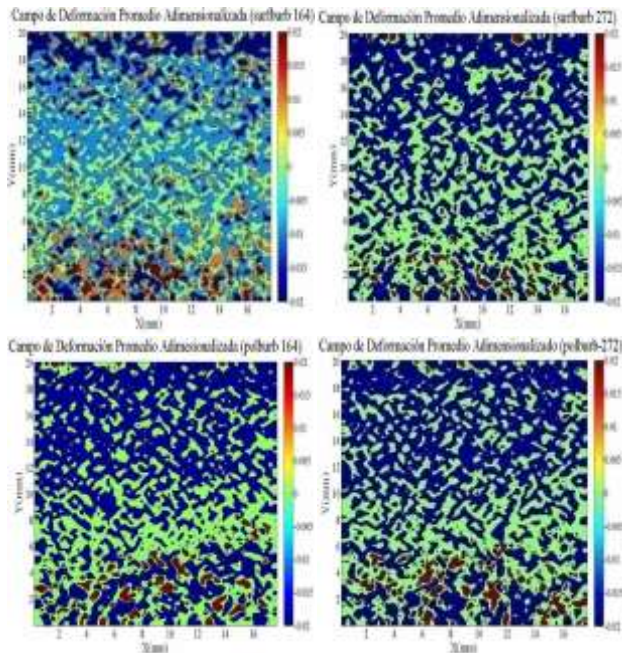

Figure 11 Deformation fields for bubble-polymers and bubble-surfactants (164 and 272 ppm)

On the other hand Table 12 shows the strain values for the combination of bubbles with polymers for 272 ppm compared to water and their difference were also carried out in the row corresponding to y+ = 7 = 0. 484mm but the range of the values shown is from column 38 to 48, but here most of the values obtained by subtraction of the absolute values of the water strain with the absolute values of the bubble with polymer condition are positive, which means that the strain decreased in the near-wall zone with the drag reducing agents and therefore that justifies that the drag was reduced by 91%.
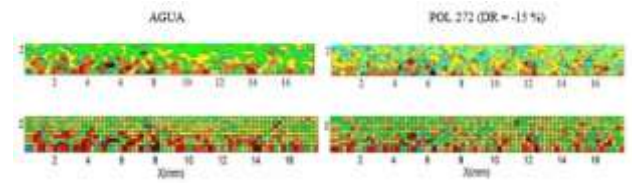

Figure 12 Comparison of Strain Fields for water and polymer at 272 ppm in the near-wall zone

Column	23	24	25	26	27
pol 272	-0.0190	-0.0176	-0.0115	-0.0162	-0.0190
Water	-0.0142	-0.0106	-0.0098	-0.0129	-0.0113
Difference	-0.0048	-0.0070	-0.0017	-0.0033	-0.0077
Condition	Increases	Increases	Increases	Increases	Increases
Column	28	29	30	31	32
pol 272	-0.0077	-0.0033	-0.0168	-0.0122	-0.0192
Water	-0.0131	-0.0183	-0.0162	-0.0145	-0.0044
Difference	0.0054	0.0150	-0.0006	0.0023	-0.0148
Condition	Decrease	Decrease	Increases	Decrease	Increases

Table 11 Strain values for water, polymer at 272 ppm, their difference and condition.
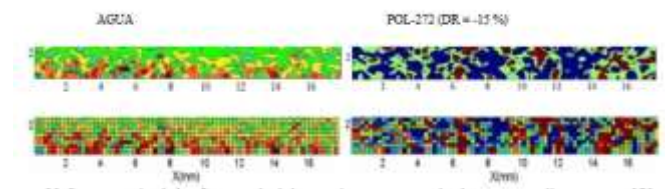
Figure 13 Comparison of Strain fields for water and bubbles with polymer at 272 ppm in the near-wall zone

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Column	38	39	40	41	42	43
polburb 272	0.006	-0.007	-0.015	-0.006	-0.027	-0.022
Water	0.011	-0.013	-0.018	-0.016	-0.014	-0.004
Difference	0.005	0.006	0.004	0.010	-0.013	-0.018
Condition	Decrease	Decrease	Decrease	Decrease	Increases	Decrease
Column	44	45	46	47	48	
polburb 272	-0.005	0.009	0.012	-0.011	-0.020	
Water	-0.008	-0.018	-0.015	-0.024	-0.018	
Difference	0.004	0.009	0.003	0.013	-0.002	
Condition	Decrease	Decrease	Decrease	Decrease	Increases	

Table 12 Strain values for water, polymer with water 272 ppm, their difference and condition

Table 13 shows the average strain values for all conditions at y+ = 7 = 0.48mm located in the buffer sublayer, which increased or decreased and were also compared with the drag reduction, for example for the conditions where bubbles, polymers, polymers with bubbles and polymers with surfactants were added for 164 ppm 46.57 % of the strain values increased and 53.42 % decreased giving 69.12, 0.052, 82.01 and 46. 98 % in drag reduction respectively, for the conditions where the surfactant with bubbles combinations are added for both 164 and 272 ppm 42.46 % of the values increase and 57.53 % decrease having a drag reduction of 37. 36 and 16.16 % and for the conditions where surfactants were added for 164 and 272 ppm 47 .94 and 45.89 % of the values increased and 52.05 and 54.1 % decreased respectively, while in the case of bubbles 46.57 % increased and 53.42 % decreased.

It is evident that in all the above mentioned conditions there was a higher percentage of the average strain values that decreased to those that increased when compared to the condition where no drag reducing agents were worked. On the other hand in the cases where the drag increased the percentage of the strain values decreasing is lower than those increasing when compared to the solvent (water) values for example for the condition where polymer was added independently for 272 ppm there was an increase in drag reduction of 15 % due to 72. 6 % of the strain values increased and only 27.39 % decreased and finally for the condition where polymer was added with surfactant for 272 ppm 57.53 % of the strain values increased and 46.46 % decreased, therefore there was an increase of 24.9 % of the drag.

Condition	Increases (%)	Decreases (%)	DR (%)
Bubbles	46.57	53.42	69.12
Surfactant(164ppm)	47.94	52.05	11.47
Surfactant(272ppm)	45.89	54.1	7.58
Polymer (164ppm)	46.57	53.42	0.052
Polymer (272ppm)	72.60	27.39	-15.1
SurfBurb(164ppm)	42.46	57.53	37.36
SurfBurb(272ppm)	42.46	57.53	16.16
PolBurb(164ppm)	46.57	53.42	**82.01**
PolBurb(272ppm)	45.20	54.79	**93.10**
PolSurf(164ppm)	46.57	53.42	46.98
PolSurf(272ppm)	57.53	46.46	-24.9

Table 13 Percentages of strain values increasing or decreasing at y+ = 7 =0.48 mm for different working conditions

Conclusions

The average velocity profiles and also the average deformation fields were determined for each condition, where it was observed that when drag reducers were added, the velocity and deformation did not have a tendency, which was demonstrated in the maximum velocity variation graphs and in the deformation fields. When drag reducing agents were added, bubbles, surfactants, polymers and the combinations bubbles with surfactants, bubbles with polymers and surfactants with polymers, the velocity increased considerably from 30% to 38%. However, when only polymers were added the maximum velocity increased less than 3% for 164 ppm and increased 5% for 272 ppm.

On the other hand, the average deformation in the far wall zone (y > 2 mm) increased by 2 to 3 times when only cationic surfactant (sulfate-free shampoo) was added, contrary to what occurred when only polymers were added, where it can be considered that the deformation fields did not change considerably with respect to the polymer condition.

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When bubbles or their combinations were used with the concentrations 164 and 272 ppm of surfactant (sulfate-free shampoo) in the same zone far from the wall (overlapping sublayer and outer sublayer) increased from 2 to 4 times.

However, in the zone close to the wall and < 2mm (viscous and buffer sublayer) the deformation did not behave in the same way as in the zone far from the wall (overlap sublayer and outer sublayer) because although there is no trend, it could be seen in Table 13 that the deformation decreases when the drag reduction increases. This is logical because the shear stress also decreases, for example, in the conditions where the highest percentages of drag reduction were obtained, which were when bubbles and polymers with bubbles were added for 164 and 272 ppm, it can be seen that the deformation at the point $y+ = 7 = 0.48mm$ decreases between 53 to 55 %.

However, it is possible that the reason why a trend was not found was because the results shown in Table 13 belong only to a point in the damping sublayer and also the viscous sublayer could not be appreciated, so it is recommended to make a more thorough study of the near-wall region especially of the viscous and damping sublayers since it is possible that the reduction of the deformation in that area explains the reduction of the drag so high obtained under these conditions.

When only bubbles were used, there was a considerable increase in the drag reduction of 70% and the combinations of bubbles with polymers (polyox WSR - 301) had the best results in drag reduction of 82 and 93% for the concentrations of 164 and 272 ppm respectively, while when combinations of bubbles with surfactants were used, the results were 37 % for 164 ppm and only 16 % for 272 ppm, and for the combination of polymer with surfactant for 164 ppm the results were 47 % and for 272 ppm the drag increased by 25 %, possibly due to an incorrect preparation of the polymer or surfactant.

Therefore, it is concluded that the greatest synergistic benefit is presented when combining the bubble drag reducer and polymer techniques, which consists of the fact that the polymers (polyox WSR - 301) break the surface tension and this facilitates the injection of the bubbles in the buffer sublayer and in turn the bubbles contribute to the polymers to be transported in an orderly manner in the area near the wall, therefore both techniques help each other. But it is necessary to make an energy study since it must be considered that the addition of bubbles (injected by electrolysis) and polymers consumes more energy than the addition of only one, and it will be necessary to see if more energy is saved than consumed when both techniques are used.

Nomenclature

A	Cross-sectional area of the channel [m2].
D	Microbubble diameter [µm].
DHydraulic	Hydraulic Diameter of the channel [m] [m] [m
DR%	Percentage of drag reduction [%] [%] [%] Friction coefficient
F	Friction coefficient
f_s	Solution friction coefficient
f_N	Coefficient of friction of solvent without friction reducing agents
fpx	Pixel equivalence in millimeters
G	Acceleration due to gravity
IAI	gravity [m/s2] [m/s2
PIV	Size of interrogation area
pol 164	interrogation area size [pix]
pol 272	Image velocimetry of
polburb 164	particles
polburb 272	polymer at 164 ppm concentration
Ppm	polymer at 272 ppm concentration
ΔP_s	polymer with bubbles at 164 ppm concentration
Surf 164	Polymer with bubbles at 272 ppm concentration
surf 272	parts per million
surfburb 164	Solution pressure drop
surfburb 272	Surfactant at τwater concentration 164 ppm
surfpol 164	surfactant at τpared concentration 272 ppm
surfpol 272	Surfactant-bubble combination for a concentration of 164ppm
tajuste	bubble for a concentration of 164ppm
u^+	Surfactant-bubble combination for a concentration of 272ppm
u_τ	bubble for a concentration of 272ppm
$\overline{u}$	Surfactant-polymer
umax	polymer for a
X	concentration of 164ppm
Y	Surfactant-polymer combination
y+	polymer for a
Z	concentration of 272ppm

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