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Influence of Polymer Solution on Pump Performances

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Abstract

In professional warewashing machines, as for example the model of Electrolux Rack Type, the working conditions of the pump are affected by the operating fluid properties, which are different from those of pure water. In fact, the actual trend in this kind of professional appliances is to reduce both energy consumption and time needed for cleaning process: this involves short washing cycles conducted at low temperatures with a solution of water and highly concentrated chemistry. Detergents contain different components and additives, as polymers and surfactants, which can affect the performance of the pump, including cavitation inception conditions. Cavitation leads to flow instabilities, affecting pump performances and inducing an increment in the level of vibrations and noise. While cavitation phenomena in Newtonian fluids is well known, particularly as far as pure water is concerned, in literature there are also various studies on cavitating flows in presence of diluted solutions of polymers additives in water, but only few studies are available regarding the effect of detergent components on pumps cavitation and, in general, on pumps performances. The wide range of variables affecting the phenomenon has led to the development of a laboratory rig for testing centrifugal pumps with aqueous solutions representative of those used in the warewashing sector [1]. This paper presents the results of tests performed with various solutions of a polymer (Polyox WSR301) in water. A rheometric analysis has been previously performed on samples of some of the tested solutions, for characterizing their behavior in terms of both viscosity in laminar conditions and their classification as "diluted" or "concentrated". For each solution, the resulting performance curves of the pump are then compared with those obtained with pure water.

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Keywords: Pump performances, polymer solutions

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1. Introduction

A centrifugal pump in the hydraulic circuit of a warewashing machine ensures fluid flow circulation as well as the kinetic energy needed for the soil removal. The operating fluid is a solution of detergents in water, and chemistry, mechanics, temperature and time are the four main factors that guide the cleaning process. These factors and their interactions are visible in the Sinner's circle [2]. The actual trend in professional dishwashing machines is to reduce both energy consumption and time needed for the cleaning process: this involves short washing cycles conducted at low temperatures [3] with a solution of water and highly concentrated chemistry, which is processed by the pump. This high concentrated chemistry could have significant impacts also on pump performance and cavitation inception. Indeed, a cleaning product is characterized by different components as surfactants, alkalis, acids, builders and other substances that affect the water-detergent solution properties in various manners [4], [5]. In particular, polymers could have an influence on the cavitation inception [6] and on pump performances [7], [8],[9], [10] the last effect being mainly due to drag reduction, in particular at high Reynolds numbers, that can be enhanced by the presence not only of polymers [11], but also of surfactants. Drag reducing effect was discovered by Toms in 1948 [12] stating that a small concentration of poly(methyl methacrylate), approximately 10 ppm, showed a substantial reduction of the friction factor, even if the viscosity and density of the polymer solution only slightly diverged from those of the pure solvent. When polymers are added into turbulent flows, they are subjected to local flow conditions that induce flow orientation, chain stretching and relaxation. The result of these structural changes is evident as an intrinsic elastic stress, which alters the flow field [13]. In particular, the dynamics of the near wall turbulent structure influences the momentum transfer into the wall that, in macroscopic scale, is seen as a reduction of the friction factor [11]. The last one is a dimensionless pressure gradient that, for a given plant, is a function of only the Reynolds number for fully developed flow of Newtonian fluids. Good drag reducing agents are characterised by long and flexible chain backbone. Considering two distinct polymers having the same molecular weight and configuration, linear polymers will be more effective than branched polymers. Furthermore, polymers formed by low molecular weight monomers will have a greater drag reduction [12]. The object of this work, as a part of the wider research regarding the overall analysis of pumps operating with detergent solutions and the monitoring of cavitation inception, is to analyse the rheology of water - Polyox WSR 301 solutions and to evaluate their effects at different concentrations on the performances of a pump for professional appliances.

Nomenclature			
η	viscosity $[Pa\ s]$	g	gravitational acceleration 9.807[m/s^2]
ρ	density $[Kg/m^3]$	σ	shear stress $[Pa\ ]$
Q	fluid flow $[m^3/s]$	$\dot{\gamma}$	shear rate $[s^{-1}\ ]$
H_T	total head $[[m]]$	$NPSH_a$	Net Positive Suction Head Available $[m]$
V	tension $[V]$	$NPSH_r$	Net Positive Suction Head Required $[m]$
I	current $[A]$	p	pressure $[bar]$
η_s	viscosity pure solvent $[Pa\ s]$	Δz	height difference (delivery-aspiration) $[m]$
η_0	viscosity polymer solution $[Pa\ s]$	u_s	fluid velocity suction $[m/s]$
$\eta_{sp,0}$	specific viscosity	u_d	fluid velocity delivery $[m/s]$
c	concentration $[ppm]$	Δp	pressure difference (delivery-aspiration) $[bar]$
H	relative increment of H_T with c [%]	c^*	overlap concentration $[ppm]$
P	relative increment of power with c [%]	MHP	Maximum Head Point
E	relative increment of efficiency with c [%]	BEP	Best Efficiency Point
C	relative increment of $NPSH_r$ with c [%]	p_v	vapour pressure $[bar]$
		p_s	pressure at pump suction $[bar]$

2. Flow loop

A test rig has been designed according to the International Standard 9906:2012 [14] and other literature studies [15], [16]. It allows measuring the characteristic curves and $NPSH_r$ of different pumps, with various fluids (e.g. water - polymers solution and detergent at different concentrations). The pump is installed in a closed circuit, as presented in Fig.1, whose main pipes have external diameter DN 65. In the $NPSH_r$ test the fluid flow is fixed and the $NPSH_a$ is progressively reduced. Such reduction is achieved acting on the pressure of the free surface level in the tank, until a specific value of pressure is reached. In this plant it is also possible to induce cavitation at a fixed fluid flow by changing the water temperature by means of two electric resistances (one of 17 kW and the other of 9 kW).

The tests have been performed at a fixed rotation speed of the pump (2900 rpm). A 3% head decrease at a certain fluid flow has been considered as cavitation signal [15], [14]. The tank is designed to avoid inclusions of gases in the suction of the pump. Inside the tank are installed two calm screens, a spray nozzle device and the connection to a vacuum pump. The fluid-free surface pressure is measured with a vacuum-pressure gauge. Two relative pressure transducers by Trafag are positioned at a distance of two diameters from suction and outlet sections of the pump (symmetric uncertainty on the confidence level of 95 % is 0.002 bar, precision 0.15% on full scale). The aspiration transducer has a measurement range of ±1 bar (power supply: 24 V-DC, signal output: 4-20mA) instead the pressure transducer at the delivery has a measurement range between 0 bar and 2.5 bar (power supply: 24 V-DC, signal output: 10 V-DC). The pump flow rate is measured with an electromagnetic flow meter provided by Endress Hauser with a measurement interval 0 – 950 l/min (power supply 230 V-AC, output signal 4-20mA, error 0.5% on the read value). Flow meter measurements accuracy is reached positioning the flow meter after ten diameters from the pipe curve and at five diameters from the branch to the deaeration nozzle. The flow rate regulation is obtained by throttling the valve 2 in Fig. 1.a, installed in the discharge pipe. The pump is driven by a three-phase AC electric motor of 2.2 kW. A twelve diameters length straight transparent Plexiglas pipe is installed at the suction side of the pump, for reaching a uniform distribution of velocity and pressure. Another transparent Plexiglas pipe is also positioned at the delivery section of the pump. These transparent pipes are used for visualising the fluid in cavitation conditions. The temperature of the solution in the tank is measured with a Pt100 (symmetric uncertainty on the confidence level of 95 % is 0.2 °C, measurement interval is – 50°C - 600 °C) and a K thermocouple is used for monitoring the resistance temperature. All the measurements are acquired by means of a LabVIEW® controlled N.I. CompactRIO® system, and the data are then processed with MATLAB® codes. A Yokogawa digital power meter is used for measuring the electric parameters (accuracy ± 0.1% in reading, + 0.05 of range).

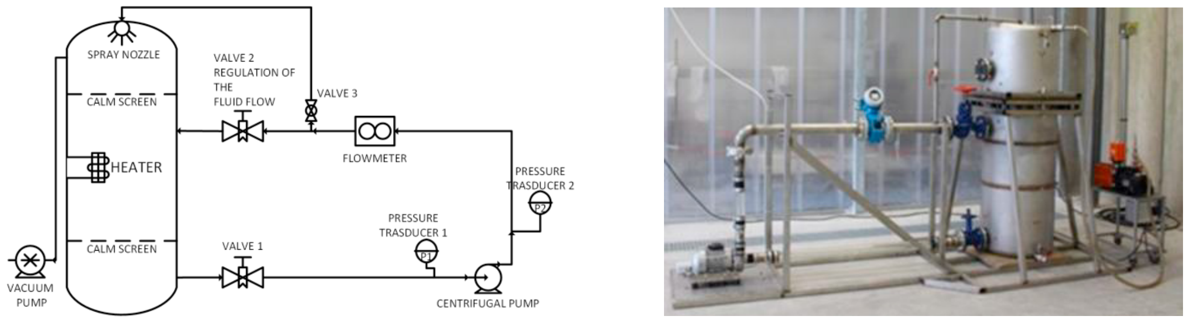

Figure 1: a) Functional scheme of the test rig b) Picture of the test rig

3. Experimental phase

3.1. Fluid characterization

A polymer is a high mass macromolecule, composed by a certain number of repeating units (monomers) which form chains, whose length is proportional to the number of monomers present in the macromolecule [11]. Polymers normally form random coils. A coil stretch transition happens to a polymer chain if an external force is applied and a critical value is exceed such that the polymer will deform proportionally to the strength applied [11]. Depending on the concentration of polymers in the solvent, it is possible to define two solution regimes: diluted and concentrated. In a diluted polymer solution, intramolecular interactions control the conformation of the individual chains while the interactions between coils are negligible, i.e. there is no overlapping between the chains. Instead, in a concentrated regime every chain influences the nearest ones, so that there is an overlapping phenomenon between the polymer coils. Going from one regime to the other, the viscosity of the solutions varies according to different law scale.

Doubling the concentration, in a diluted solution the viscosity increases its value quite proportionally instead, at concentrated regimes, viscosity increases ten or more times over. The solutions of WSR 301 used in this work have been tested with a modular rheometer platform (Thermo Scientific Haake Mars Rheometers) [17] with the aim of identify the concentration values at which they switch from the diluted to the concentrated regime. In Fig. 2 a bi-logarithmic representation of the obtained results are shown in terms of viscosity as a function of a) the measured shear stress and b) the applied shear rate.

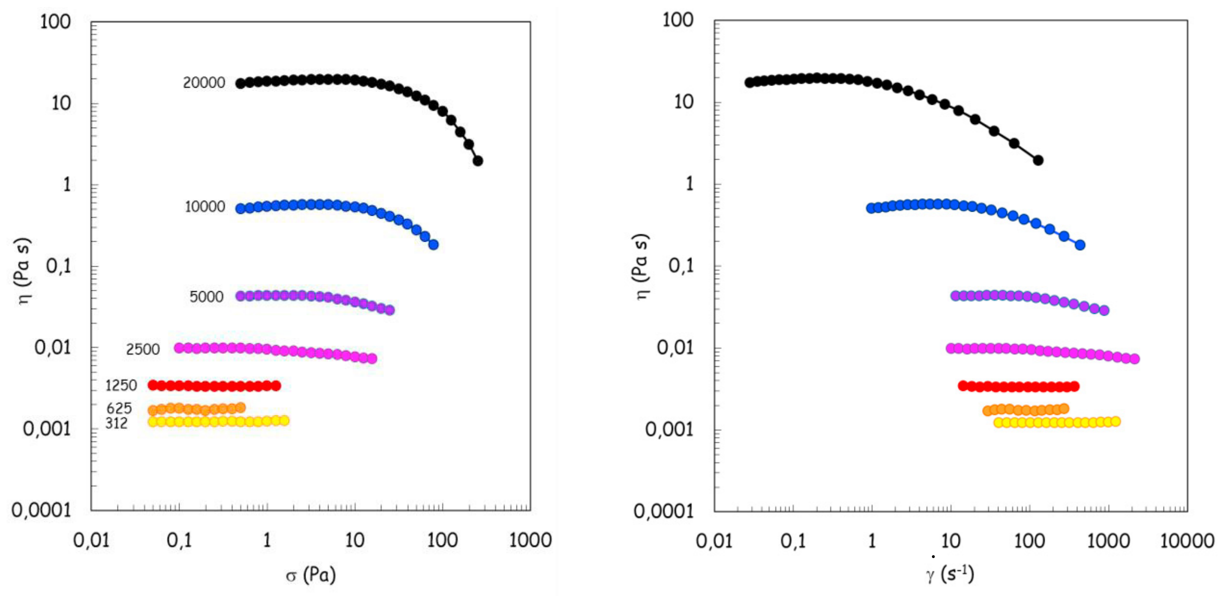

Figure 2: Experimentally measured a) shear stress-viscosity b) shear rate- viscosity of different WSR 301 solutions

The solutions have been obtained doubling the dilution degree starting from a maximum concentration of 20000 ppm, so the successive considered values have been 10000, 5000, 2500, 1250, 625 and 312 ppm, respectively. The rehometer tests can cover only laminar flow conditions and, as long as viscosity is practically constant, the tested fluid behaves as a Newtonian fluid. From 312 ppm up to 1250 ppm, the solutions of Polyox WSR 301 meet this requirement, while from 2500 ppm up, the behavior of the solutions appear to be of the so-called shear thinning type. The diluted and concentrated regimes can be better recognized using these results to define the specific viscosity, Eq.1, where η_0 is the viscosity of the polymer solution and η_s is the viscosity of the pure solvent (water in this case).

$$\eta_{sp,0} = \frac{\eta_0 - \eta_s}{\eta_s} \tag{1}$$

Fig. 3.a shows the trend of η_0 and Fig. 3.b that of $\eta_{sp,0}$ at increasing concentration values. The last one highlights the overlap concentration, c^*, defined as the upper limit between diluted regime and concentrated regime. The corresponding power laws of viscosity are, for the diluted regime, $\eta_{sp,0} \propto c^{1.3}$ and, for the concentrated, $\eta_{sp,0} \propto c^{5.1}$.

As previously said, these results, useful to classify the solutions used in the successive tests on the rig, have been obtained in laminar regimes, while it is well known that pumps usually works at high Reynolds number, in turbulent regimes. The effects on drag coefficient of polymer concentration is more evident in such regimes, as shown in Fig. 4 [12] , which highlights the behavior of friction factor of water with or without a small amount of poly(ethylene oxide) in dependency of the Reynolds number.

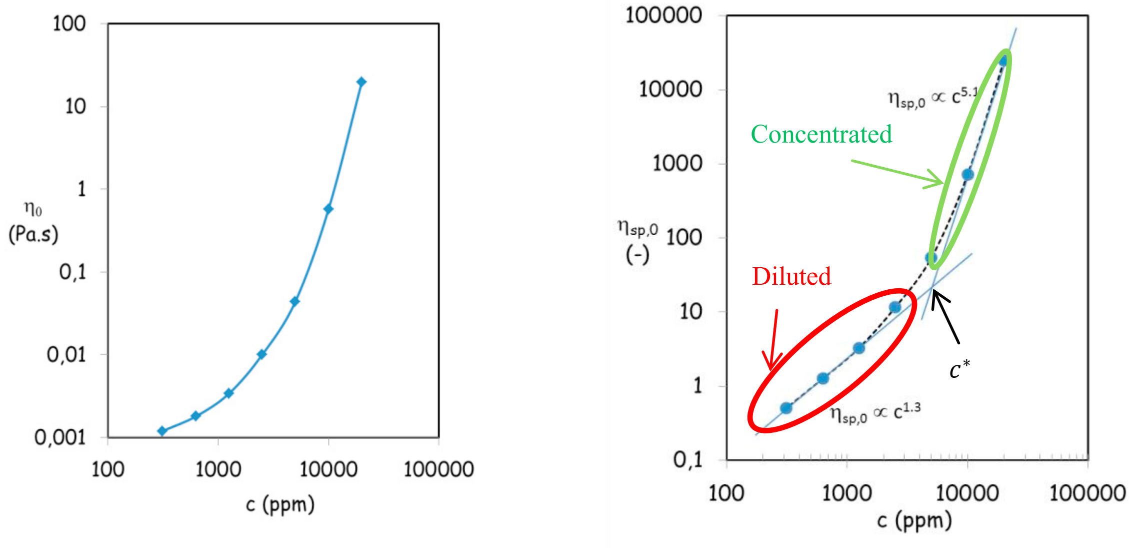

Figure 3: a) Trend of the viscosity solution; b)Trend of the specific viscosity in dependency of the solute concentration

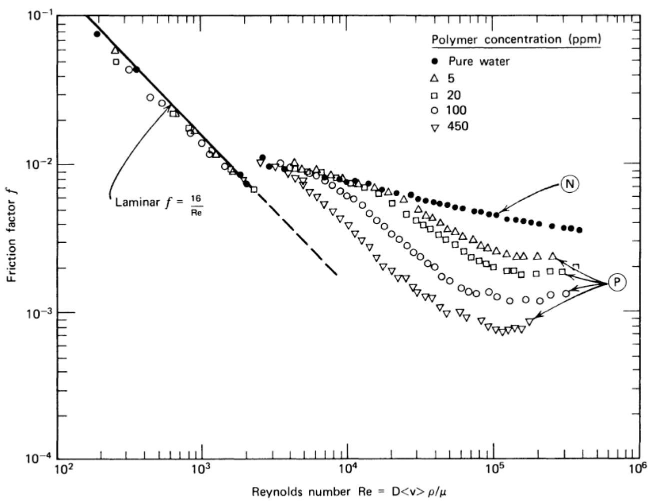

Figure 4: Friction factor for dilute aqueous solutions of poly(ethylene oxide)[12]

3.2. Pump characteristic curves

The tests have been performed at eight fluid flow values, from 100 l/min up to 800 l/min with a step of 100 l/min. The sampling frequency was 12800 Hz. Eq. 2 gives the total head of the pump:

$$H_T = \frac{\Delta p}{\rho g} + \frac{u_d^2 - u_s^2}{2g} + \Delta z \qquad (2)$$

where Δp is the pressure difference between the pump delivery and suction sections, u_d is the velocity at the delivery while u_s is the velocity at the suction. These velocities are calculated according to the measured flow rate and the diameters of the corresponding sections. The density ρ is calculated on the basis of the temperature measured during the test and Δz is the height difference between the two pressure transducers. The total efficiency of the pump is calculated according to the following formulation:

$$\eta = \frac{\rho g Q H_T}{\sqrt{3VI}} \tag{3}$$

where V and I are the voltage and intensity of the current measured at the pump electric motor. The required net positive suction head, H_r , is defined in the following Eq.4:

$$NPSH_r = \frac{p_s}{\rho g} + \frac{u_s^2}{2g} - \frac{p_v}{\rho g} \tag{4}$$

where p_v is the vapor pressure at the test temperature and p_s is the pressure at the suction section of the pump.

4. Results and discussion

The first tests, to which this work relates, were made at four concentrations of Polyox WSR 301, falling in the diluted solutions, i.e. 100, 200, 400 and 800 ppm, and one around the lower limit of concentrated solutions, namely 7000 ppm. Total head, absorbed power, efficiency and *NPSH$_r$* of the pump obtained with pure water and with the solution at 800 ppm, which has led to the higher performance among the tested ones, are reported in Figs. 5, 6, 7 and 8 respectively.

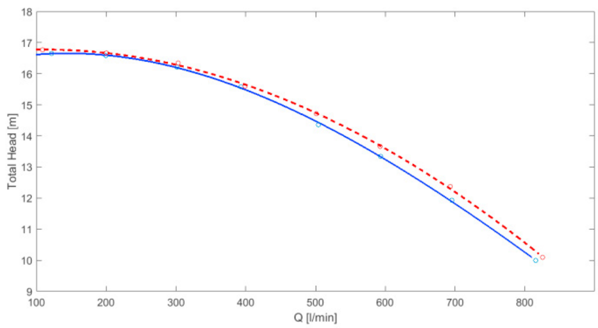

Figure 5: total head with pure water (blue) and 800 ppm solution (red)

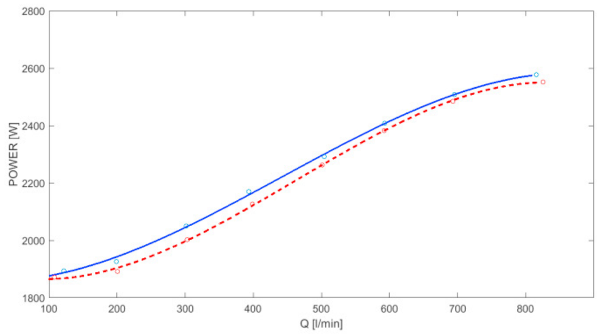

Figure 6: power with pure water (blue) and 800 ppm solution (red)

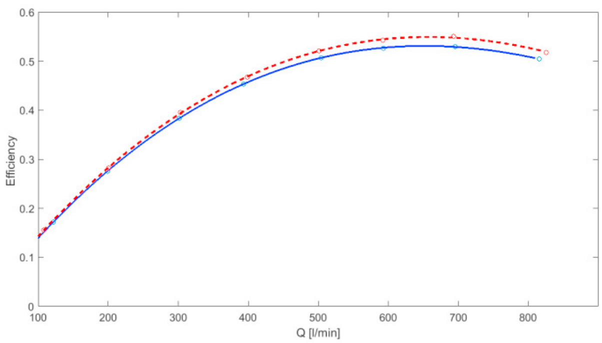

Figure 7: efficiency with pure water (blue) and 800 ppm solution (red)

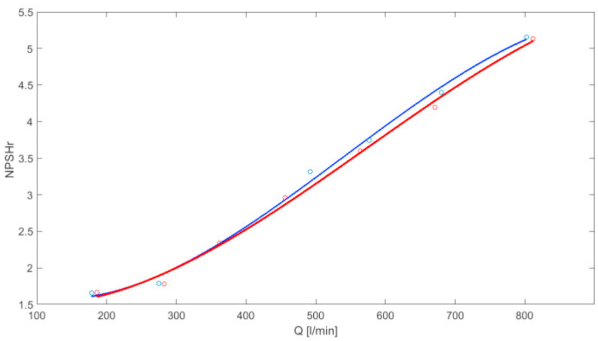

Figure 8: *NPSH$_r$* with pure water (blue) and 800 ppm solution (red)

The results obtained with all the tested fluids for the various performance parameters are given, instead, in terms of percentage of normalized differences, i.e. of difference between the value obtained with the considered solution and that obtained with pure water divided by the last one, expressed in %. Such percentages are calculated for the mass flow rate of maximum efficiency with water (Best Efficiency Point – *BEP*) and for that of maximum total head (Maximum Head Point – *MHP*). The symbols used for the various parameters are H, P, E and C for total head, absorbed power, efficiency and $NPSH_r$, respectively. Figs. 9, 10, 11 and 12 report the values of H at *MHP* and of P, E and C at *BEP* as a function of the concentration of polymer, on a logarithmic scale.

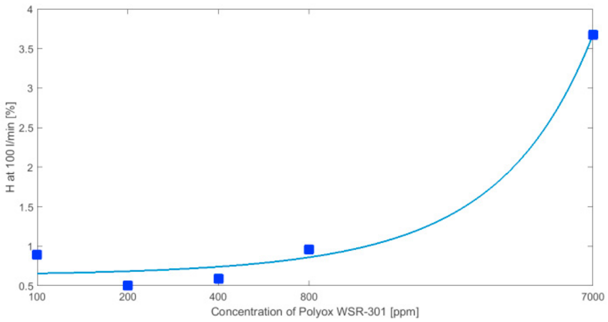

Figure 9: relative increment of total head with solutions, H, at *MHP*

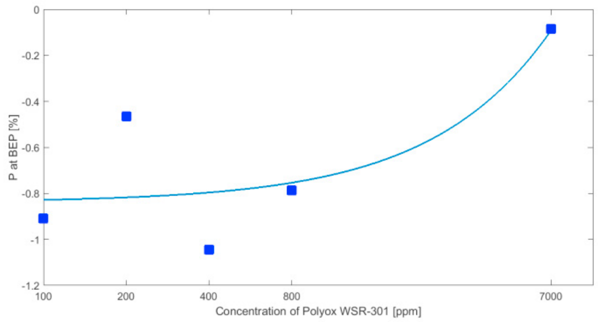

Figure 10: relative increment of power with solutions, P, at *BEP*

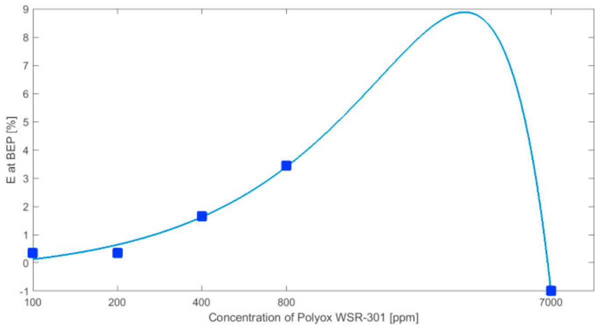

Figure 11: relative increment of efficiency with solutions, E, at *BEP*

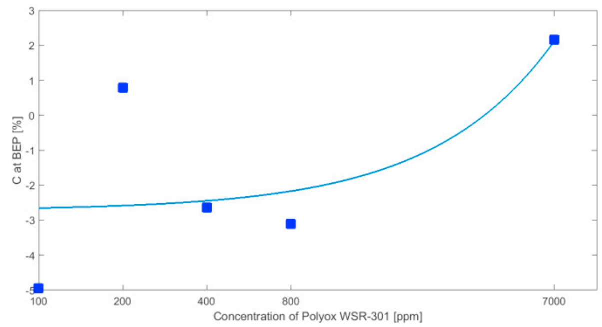

Figure 12: relative increment of $NPSH_r$ with solutions, C, at *BEP*

The results of the experimental analysis show that at low concentration, the presence of polymers leads to a relatively large improvement of efficiency, especially at high flow rates, and to a slightly less evident increment of total head. On the contrary, at the highest concentration of the solution, the total head increases of more than 3.5% at *MHP* but efficiency at *BEP* decreases: to clarify these contradictory trends other tests are required, with polymer concentrations intermediate between 800 ppm and 7000 ppm. These results are as a whole aligned with the literature experimental trends. In [7] literature results are discussed showing that polymeric additives yields higher head (at a given flow rate), higher efficiency and lower required power. The author found, in his experimental analysis on the centrifugal pump of a waterjet, that with only 10 ppm of polymer concentration there was a 7% head increase and a 9% efficiency increase and that, generally, efficiency increases more than head, especially toward higher rpm. This can be due to a reduction in some internal losses of the pump, as disk and casing friction [7] [9][10], which affects more the overall efficiency of the pump than the energy usefully transferred to the fluid. In [18] efficiency improvements were between 6% and 9%. In [9], with a 20 ppm solution, maximum efficiency was increased of 12% while the head coefficient remained almost the same, when compared with the pure water values. At speeds higher than the design one, polymer should become less effective in presence of stronger viscous dissipation due to high turbulence levels in the blade channels, but its effectiveness could remain in reducing the clearance viscous dissipation, leading to more significant efficiency increment, as reported in [7]. Results regarding the $NPSH_r$ values are difficult to interpret both because the experimental data are too few and do not show a clear trend and because the authors have not been able to found comparative data in literature.

5. Conclusion and further work

The experimental rig developed to test pumps used in washing circuits of professional appliances has proven to be flexible and reliable. The first step in the analysis of the performance in terms of total head, efficiency and cavitation requirements with water-detergent solutions has been a series of tests using some diluted and one concentrated solution of a polymer, the Polyox WSR 301, representative of a class of substances that are usually found in the composition of detergents. The definition of diluted or concentrated solution has been based on preliminary rheological tests carried on in laminar conditions for a systematic series of samples of various polymer concentration. The results are as a whole in accordance with the not very numerous comparable data found in literature: at low concentration, the presence of polymers leads to a relatively large improvement of efficiency, especially at high flow rates, and to a less evident increment of total head. This can be due to a reduction in some internal losses of the pump, as disk friction, that are substantially independent from the exchange of energy between machine and fluid in the blade channels. At higher concentrations of the solution, such advantages seem to reduce, but, of course, other investigations are needed. The results obtained as far as the variation of cavitation margin is concerned are, at the moment, quite doubtful, because the few data so far obtained doesn't show a clear trend and, to the knowledge of the authors, there are no comparative data available in literature.

Future steps of the analysis will be the completion of the tests using smaller concentration step amongst the solutions and the evaluation of the pump performances with another polymer (WSR 308) and a detergent (ECOLAB). Furthermore, sound and vibration data, especially in conditions of incipient cavitation, have already been sampled during the tests and their collection will continue in the future. These data will be processed, considering in particular the energy level (RMS) at distinct frequency ranges and the statistical moments of the signal, both in time and frequency domains. Such information will be used to develop reliable control and monitoring strategies to ensure the safe operation of professional appliances.

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