Experimental analysis of the influence of polymer solutions on performances and cavitation of small size pumps for professional appliances

Fabio Burlon[1,2], Diego Micheli[1], Michele Simonato[3] and Riccardo Furlanetto[4]

Abstract

Pumps used in professional appliances process a solution of water, soils residues and detergents. These affect vapor tension, viscosity and rheology of the solution, mainly due to the presence of surfactants and polymers. Only a few studies have been found on how these substances can influence pump performances. Therefore, an experimental analysis has been carried out with aqueous solutions of a detergent component, the Polyox WSR 301, in the concentration range of 100–7000 ppm, to evaluate their influence on pump performances and cavitation. Some properties of the solutions have been preliminary characterized with a rheometer. Then, each solution has been tested in a dedicated test rig, to compare the performance curves of a centrifugal pump used in professional warewashing machines with those obtained with pure water. A non-intrusive method, based on the investigation of high frequency vibrations and noise signals, has been developed to detect cavitation at its early stage of inception. It was observed that polymer mitigates cavitating pump vibrations, with a reduction of the acceleration to less than one g. The analysis has provided the data necessary for the successive development of a control strategy for pump operation in professional appliances.

Keywords

Pump performances, polymer solutions, cavitation inception, condition monitoring, non-Newtonian fluid

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Introduction

In professional appliances, centrifugal pumps provide the flow rate and the kinetic energy necessary for removing the soil. These pumps process a solution of detergents in water. The cleaning process is performed by the combination of four elements: time, temperature, chemistry and mechanics. The synergy among these factors is presented in the Sinner's circle.[1]

The current tendency is to use concentrated chemistry in brief cleaning cycles performed at low temperatures, in order to reduce time and energy consumption.[1] Cavitation inception and pump performances could be influenced by this trend. Indeed, a cleaning product is a mixture of builders, surfactants, acids, alkalis, and other substances that influence in various manners the properties of the solution.[1] Polymers, in particular, could have an influence on pump performances[2–5] mainly due to the drag reduction caused by their presence, especially at high Reynolds numbers. As reported in Bird et al.,[6] this effect was declared by Toms in 1948, observing that a small concentration of poly methyl methacrylate, approximately 10 ppm, diminished the friction factor, also if density and viscosity of the solution had a minor variation compared to the pure solvent. A turbulent flow field is altered when polymers are present in the solution due to a generated intrinsic elastic stress. This is caused by local conditions that orientates, relaxes and stretch the polymer chain. The momentum transfer to the flow surface area is influenced by the dynamics of the turbulent structures near the wall that results in the reduction of the

[1]Department of Engineering and Architecture, University of Trieste, Trieste, Italy
[2]The Research Hub by Electrolux Professional, Pordenone, Italy
[3]ASAC Srl, Cessalto, Italy
[4]IMESA S.p.A., Cessalto, Italy

Corresponding author:
Fabio Burlon, Department of Engineering and Architecture, University of Trieste, Via Valerio 10, 34128 Trieste, Italy.
Email: fabio.burlon@phd.units.it

friction factor at a macroscopic scale.[5] Long and flexible chain backbone characterizes the good drag reducing agents: in general, low molecular weight monomers forming linear polymers will bring greater drag reduction.[6]

Polymers affect also cavitation inception and development because they influence the flow kinematics.[7–11] A polymer solution has greater extensional viscosity, which is a parameter related to the resistance of a fluid against stretching or elongation and deformation.[11] It acts as inhibitor of the cavitation inception because it can reduce the flow turbulence, so that the velocity is lowered and the static pressure is raised in regions of high extension rate. In Brujan,[11] author states that noise levels at cavitation inception is lower with respect to pure water, and affirms the need for new experimental tests on cavitation behavior in non-Newtonian fluids. Another author[12] states that high frequency noise content diminishes with polymer solutions.

The object of this work is to analyze the rheology of water – Polyox WSR 301 solutions and to assess their impacts on the working conditions and cavitation behavior of a pump used in professional appliances. This study is part of a broader research on the monitoring of cavitation inception in pumps operating with solutions of soil and detergent. The Polyox WSR 301 has been chosen as representative component of detergents, according to the analysis carried out in Burlon et al.[13] The vibration signals acquired on the pump scroll at various operating conditions are carefully analyzed, in order to correlate their energy content to both the concentration of the solutions and the working points of the pump.

Materials and methods

Test fluids characterization

Polyox WSR 301 (CAS number 25322-68-3) is a polyethylene glycol with the relatively low molecular weight of 40,00,000 g/mol. It is soluble in water where it forms, at the temperatures typical of professional appliances, persistent coils.

The solutions used in this study have been characterized by means of a modular rheometer platform. Up to 1250 ppm, they behave as Newtonian fluids while at higher concentrations as shear thinning ones.[13] In presence of strength, a coil stretch transition happens in extensional flows when a critical value is exceeded.[5] In shear flows of dilute solutions, chain stretching is combined with rotation, coil interactions are negligible and viscosity increases proportionally to the polymer concentration. In concentrated solutions, polymer coils interact overlapping each other and viscosity increases much more rapidly with concentration. Figure 1[13] shows the trend with Polyox

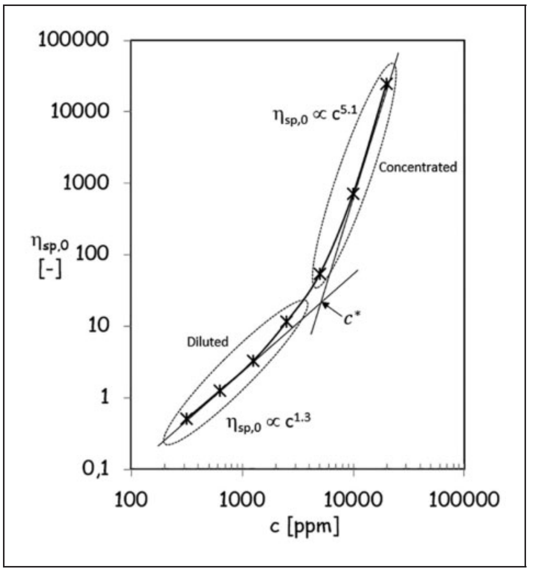

Figure 1. Specific viscosity as a function of the solute concentration.[13]

WSR 301 concentration of the solution specific viscosity, equation (1):

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

where η_0 is the solution viscosity at zero shear rate and η_s is that of the solvent. The overlapping value of the concentration, which divides the dilute regime from the concentrated one, is at about 5000 ppm.

Due to the rheometer operating principle, these results have been obtained in laminar regimes. Pumps operate at high Reynolds number, where polymers affect the drag coefficient to an even greater extent.[6]

The flow loop

The test rig, shown in Figure 2 is fully described in Burlon et al.[13] It has been realized according to ISO 9906:2012[14] and literature suggestions.[15] Pumps whose dimensions are compatible with the DN 65 pipes diameter can be tested. The specifications of the installed instruments are reported in Table 1.

In the NPSHr tests the fluid flow is constant while the NPSHa is gradually diminished, acting by means of a vacuum pump on the tank pressure, until a specific value is achieved. A 3% reduction in total head at a defined fluid flow has been associated to cavitation.[14,15] It is well known, however, that cavitation occurs with three subsequent stages, *i.e.* inception, damage and break off, and that inception happens much earlier than the 3% head decrease. Cavitation inception is revealed by the first appearance of vapor bubbles in the medium.

The damage starts somewhere beyond inception and disappears near head break down: the erosion

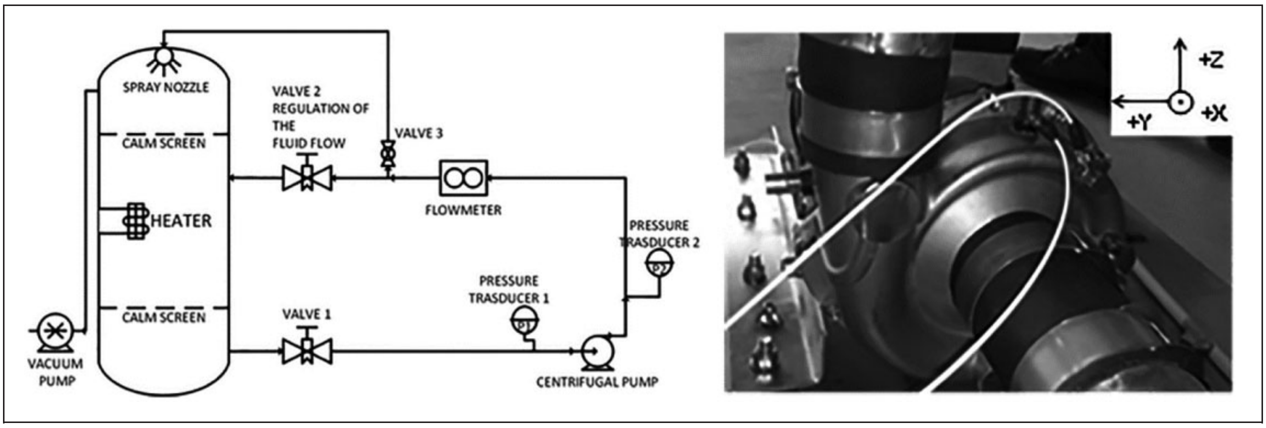

Figure 2. Test rig functional scheme and accelerometers position.

Table 1. Specifications of the instruments.

Instrument	n.	Code	Characteristics
Accelerometer	3	352C03 ICP	Sensitivity (±10%) 10 mV/g; range ±500 g; freq. range (±10%) 0.3–15,000 Hz; resonant frequency > 50 kHz
Microphone	1	130E20	Sensitivity 45 mV/Pa; frequency response (±5dB) 20–20,000 Hz; freq. response (at 0° incidence) Free-Field
Digital input module	1	NI 9234	4 Channels; ±5 V; max. sample rate 51.2 kS/s/ch; resolution 24 bit; dynamic range 102 dB
Analog input module	1	NI 9205	32 Channels; 32 ±200 mV to ±10 V; resolution 16-bit; sample rate 250 kS/s
Pressure transd. pump suction	1	Trafag NAH 8257	Range ±1 bar; output 4–20 mA; accuracy 0.15% F.S.
Pressure transd. pump delivery	1	Trafag NAH 8253	Range 0–2.5 bar; output: 0–10 V-DC; accuracy 0.15% F.S.
Temperature sensor	1	Trafag Pt100	Range –50 °C + 600 °C; accuracy 0.2 °C
Vacuum pressure gauge	1	Smc PSE530	Range 1.01–0 bar; accuracy ± 2% F.S.
Flow meter	1	Promag 50 E DN65	Range 0–950 l/min; output 4–20 mA; accuracy 0.5% of rdg
Power meter	1	WT 333	Range 5 mA–20A; accuracy 0.3% of rdg + 0.2 % of range

rate of the pump reaches its maximum between these conditions[16] because, during the head break down, the damping effect of the large number of vapor bubbles reduces the damage intensity.

These aspects of cavitation will be considered during the analysis of the sensor signals.

Measurement of the pump performances and NPSHr

The experiments have been executed at nine fluid flows, from $\varnothing/\varnothing_n = 0$ up to $\varnothing/\varnothing_n = 1.14$, where $\varnothing_n$ corresponds to 700 l/min, at the rotational speed of 2900 rpm.

Fluid flow, absorbed power and temperature measurements have been acquired at low sample frequency (10 Hz). The pressure sensors signals have been acquired at higher frequency, *i.e.* 25,600 Hz, as discussed in the next paragraphs.

Total head is calculated with equation (2):

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

The velocities at the suction and delivery sections are obtained dividing the measured flow rate for the corresponding section areas.

Equation (3) gives the total efficiency of the pump:

$$\eta_T = \frac{\rho g Q H_T}{\sqrt{3} V I} \tag{3}$$

Equation (4) defines the required net positive suction head:

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

The theory of errors propagation has been applied obtaining the uncertainty ranges of ±1% for H_T, ±0.1% for the adsorbed power and of 0.5% for NPSHr.

Measurement of vibrations and noise induced by cavitation

Vibration measurements have been acquired with three accelerometers at a sampling frequency of

25,600 Hz, as a compromise between a not overloaded measure and the capability of collecting the significant high frequency components associated with cavitation phenomena.

The accelerometers were positioned as in Figure 2, along three normal significant directions in the volute. Those positioned along the Z and Y axes acquire radial accelerations, while the sensor positioned along the X direction acquires the axial acceleration.

Pump inlet and outlet have been connected to the plant pipes with flexible joints, while the pump base was fixed on dumpers, in order to reduce the influence on the pump vibration signals of other vibrations coming out from the experimental system.

Airborne noise has been measured by means of a microphone positioned near the volute. LabView has been used for managing the data acquisition system. The same measurement facility has been also used to acquire the three pressures signals (at the pump suction and delivery and at the water tank surface level). All data have been then processed by mean of proprietary MATLAB® codes.

Measurements have been carried out continuously, decreasing slowly the NPSHa of the plant from non-cavitating to severe cavitating regimes.

Test methodology

Methods for detecting cavitation inception

There are several non-invasive monitoring/diagnostic methods for investigating cavitation inception and behavior, such as the high frequency measurement of the fluid-borne or of the airborne noise. They require the use of hydrophones immersed in the fluid, or of microphones, that can be influenced from the surrounding noise of other components.

The accelerometer signals analysis can give only relative indications, being casing dependent. It is usually adopted to monitor pump unbalances, misalignments, defective bearings etc. but it can be usefully employed also for cavitation monitoring purposes.[16]

Signal analysis has been done by means of a frequency domain technique.

Pump vibrations induced by cavitation: signal characterization

Random signals have continuous spectra, which can be analysed through the power spectral density function $S_{\alpha\alpha}$,[17] defined by equation (5):

$$S_{\alpha\alpha} = F[R_{\alpha\alpha}(\tau)] = \int_{-\infty}^{+\infty} R_{\alpha\alpha}(\tau) e^{-j2\pi f\tau} d\tau \qquad (5)$$

where $R_{\alpha\alpha}(\tau)$ is the autocorrelation given, for a stochastic time signal, by equation (6)[17]:

$$R_{\alpha\alpha}(\tau) = E[\alpha(t)\ \beta(t-\tau)] \qquad (6)$$

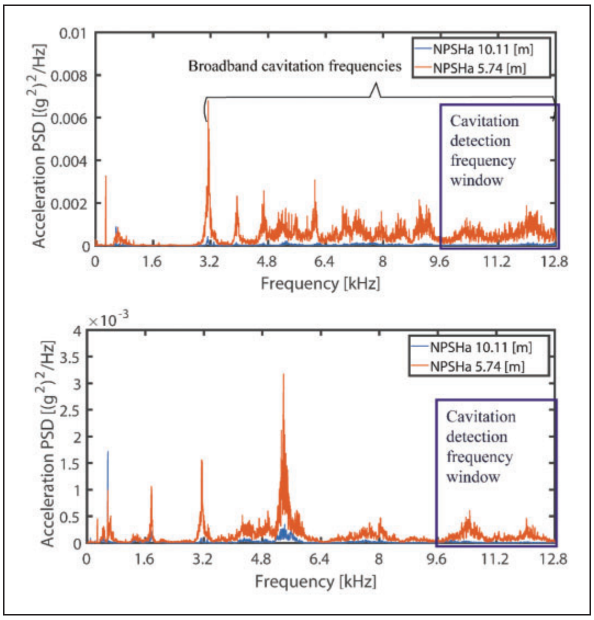

Figure 3. Power spectral density of the vibration signal in Z (top) and Y (bottom) axes ($\varnothing/\varnothing_n$=0.71).

Figure 3 shows, as an example, the power spectral densities of the accelerometer signals in the Z and Y axes, respectively, at two values of NPSHa, *i.e.*, 10.11 m, in non-cavitating regime (blue lines), and 5.74 m, at an initial cavitation stage (red lines).

The cavitation insurgence causes an increment of the peak values at all frequencies but, in particular, in the high frequency band, where in non-cavitating regime they are almost null.

These results are in good agreement with literature analysis. In Lu et al.,[18] the vibrations spectra acquired at 20 kHz with accelerometers mounted in three normal directions, as well as on the base, of a centrifugal pump show that, generally speaking, frequency bands from 6 kHz to 10 kHz can be considered typical of cavitation. In Buono et al.,[19] but with reference to a gerotor pump running from 2000 to 5000 rpm, the vibration spectra were sampled at 102.4 kHz and high energy signals due to cavitation were observed between 1 kHz and 10 kHz.

In some cases, the lower limit of the frequency band more sensitive to cavitation inception was higher, of about 10 kHz, while the upper limit was 15 kHz in Abdulaziz and Kotb[20] and Kallingalthodi,[21] 20 kHz in Wu et al.[22] and again in Kallingalthodi,[21] 25 kHz in Zhang et al.[23] and 50 kHz in Gao et al.[24]

In McNulty and Pearsall[25] and Gülich[26] authors filtered the signals in order to be sensitive enough to detect the noise increase generated by the first bubble implosion. The cutting frequency of the high-pass filter was higher than that due to the shaft and blades rotation (1 kHz in McNulty and Pearsall[25] and 10 kHz in Gülich[26]).

Interesting results are reported in literature[27–29] where very high frequency acoustic emission (AE) sensors are used to analyze a frequency range from 0.1 up to one MHz, in order to detect cavitation inception. It is shown by a steep change at high frequencies in the energy of the signal, acquired on both the pump case and the pump inlet.[27]

Because cavitation intensity can be considered proportional to the energy of the signal in the frequency band of interest, in order to better evaluate such a relationship,[24] the Root Mean Square (RMS) and Mean Square (MS) are calculated with equation (7).

$$RMS = \sqrt{MS} = \sqrt{\int 2R_{\alpha\alpha}(f)\mathrm{d}f} \qquad (7)$$

The vibration data have been analysed at different frequency bands. The power estimation has been performed using the non-parametric periodogram method.[17]

In particular, we have considered the frequency range between 10 and 12.8 kHz. This is due to both the literature findings and the analysis of Figure 3. In fact, while the frequencies in the ranges before 10 kHz showed an increasing trend of the fluctuations from the start of the NPSHa ramp down, the frequencies between 10 and 12.8 kHz showed an increase of their amplitude only below a certain value of NPSHa, assumed corresponding to incipient cavitation.

In Figure 4, it is possible to detect a change in the slope of the MS at NPSHa of about 5 m.

Between NPSHa = 5 m and 1.24 m, the vibration level achieves a maximum, corresponding to the critical vibration point,[23] detected in this case after the 3% head drop. Under 1.24 m, vibration energy decreases drastically: the noise due to the collapse of the bubbles is attenuated because the flow field becomes two-phase and then highly compressible.[23]

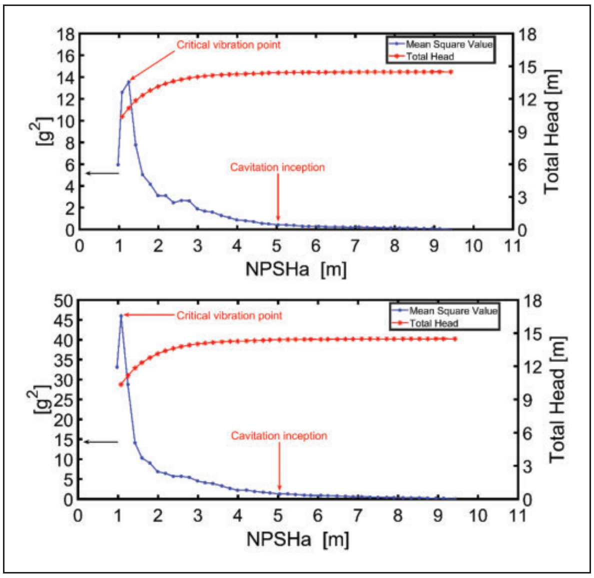

Figure 4. MS in the Y (top) and Z (bottom) axis between 10 and 12.8 kHz ($\varnothing/\varnothing_n = 0.71$, 1600 ppm).

Critical vibration point could not be assumed as the critical cavitation erosion: it corresponds rather to the peak of the high frequency noise measured by means of a hydrophone.[16]

As a whole, also the results in literature[27–29] are in agreement with that of the present work. RMS values initially increases as NPSHa decreases, but its further reductions bring to a decrement of the energy content, even if the change at cavitation inception is less steep with respect to those observed with the very high frequency noise analyzed in Neill et al.[27]

In order to evaluate if noise measurements show results similar to that obtained with the accelerometers, the results obtained by processing the external microphone signals are presented in Figure 5. The increasing of the signal attributed to cavitation inception and the following achievement of the peak value are obtained at NPSHa value identical to that highlighted in Figure 4. Also this analysis confirms the accuracy of the proposed method for analyzing cavitation development in the pump.

Figure 6 compares the RMS in the range 10–12.8 kHz of the vibration signal sampled at six flow rates and at all the three axes. The fluid is pure water. The evolution in X, Y and Z directions show similar trends at high NPSHa values, *i.e.*, without cavitation. However, when cavitation happens and progressively intensifies (at low NPSHa values) the intensification process of RMS differs in each of the three positions. Accelerometer Z reaches higher RMS values because it is closer to the region where bubbles collapse, but it is also influenced by the vicinity of the volute tongue, where the blades of the impeller create a periodically varying velocity and pressure field, as explained in Bachert et al.[15] The radial Z-axis shows higher signal values compared to the Y-axis such that it can give good relative indications of the cavitation phenomena in the pump for monitoring purposes.

Results

Influence of polymers on pump performances

The experimental campaign has been carried out at six concentrations belonging to the class of the diluted

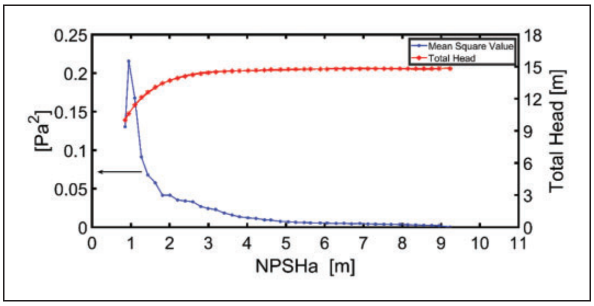

Figure 5. MS of the noise measurement between 10.0 and 12.8 kHz ($\varnothing/\varnothing_n = 0.71$, 1600 ppm).

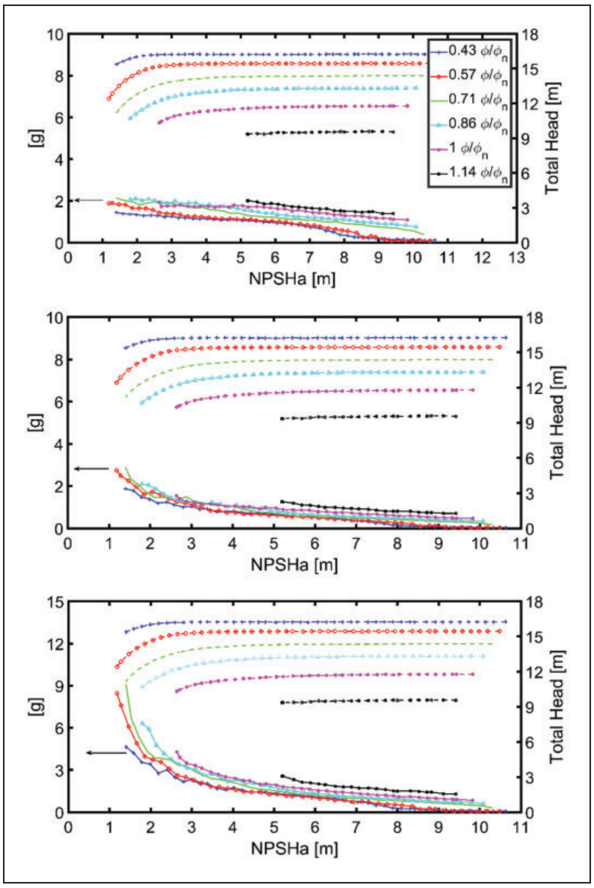

Figure 6. RMS in X (top), Y (middle) and Z (bottom) axis between 10 and 12.8 kHz, tests with water.

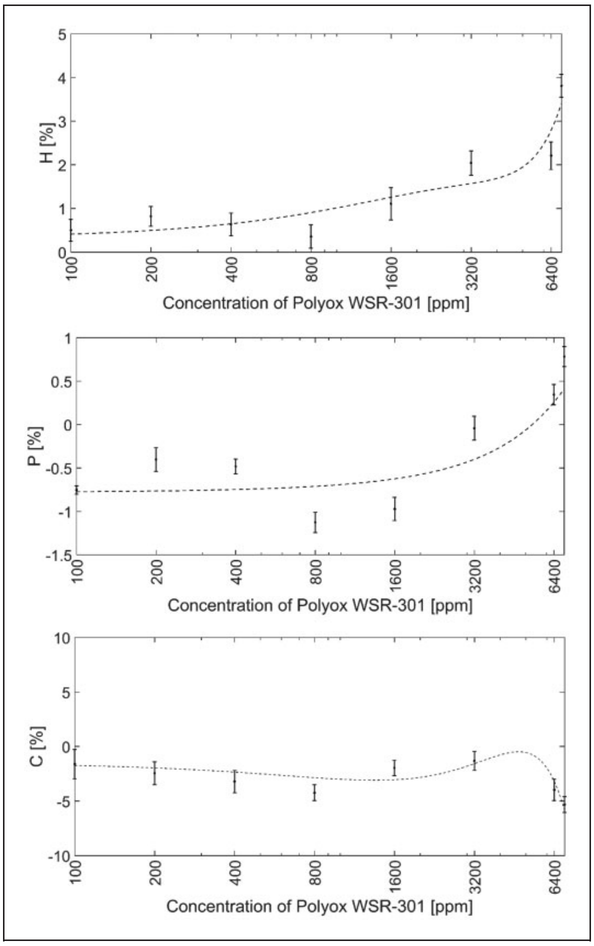

Figure 7. Relative increment of total head at MHP, H, power at BEP, P, and NPSHr at BEP, C.

solutions, *i.e.* 100, 200, 400, 800, 1600 and 3200 ppm, and two concentrations belonging to the lower limit of the concentrated solutions *i.e.* 6400 and 7000 ppm. The results are presented as percentage of the normalized differences of some parameters, *i.e.* the difference between the measured values at the considered concentration and the ones acquired with pure water, divided by the last ones.

Such percentages are calculated at the fluid flows of maximum total head (Maximum Head Point – MHP) and of maximum efficiency (Best Efficiency Point – BEP) with water. They regard the NPSHr, the total head and the absorbed power, referred to as C, H and P, respectively.

The P and C values at BEP and H at MHP obtained at the various polymer concentrations are given in Figure 7, on a logarithmic scale. The error bars refer to a 68% confidence interval.

Polymer contributes to a small improvement of total head, more evident at high concentrations, and to an almost equal trend for the absorbed power, but starting from slightly negative values at low concentrations. As a result, efficiency has very limited variations, with small but detectable improvements only at the lowest concentrations.

These results are qualitatively aligned with the literature, which refer almost exclusively to very low polymer concentrations. In Pallabazzer[2] it is shown that 10 ppm of polymer leads to 7% head increase and 9% efficiency increase in the centrifugal pump of a waterjet. Efficiency improvements between 6% and 9% are presented in Burlon et al.[13] In AbuYousef et al.[3] a study with a 20 ppm solution reports 12% increase of the maximum efficiency even though the head coefficient remains approximately equal compared to pure water. In our case, the increments of head and efficiency are lower, probably because of the polymer degradation which occurs in re-circulatory systems. Polymer degradation anticipates bubble inception and increases bubble population compared to fresh polymer solutions.[30] As shown in Toonder et al.,[31] the Polyox degradation occurs in a few minutes, particularly in presence of centrifugal pumps. Such operating conditions are significant in our case, because they are detected in both the experimental set-up and the real professional appliances.

The most significant effect of polymers could be the reduction of some internal losses of the pump, as clearance viscous dissipation and, in particular, disk and casing friction,[2–4] leading to more or less significant efficiency increments, depending on the mechanical structure of the pump.

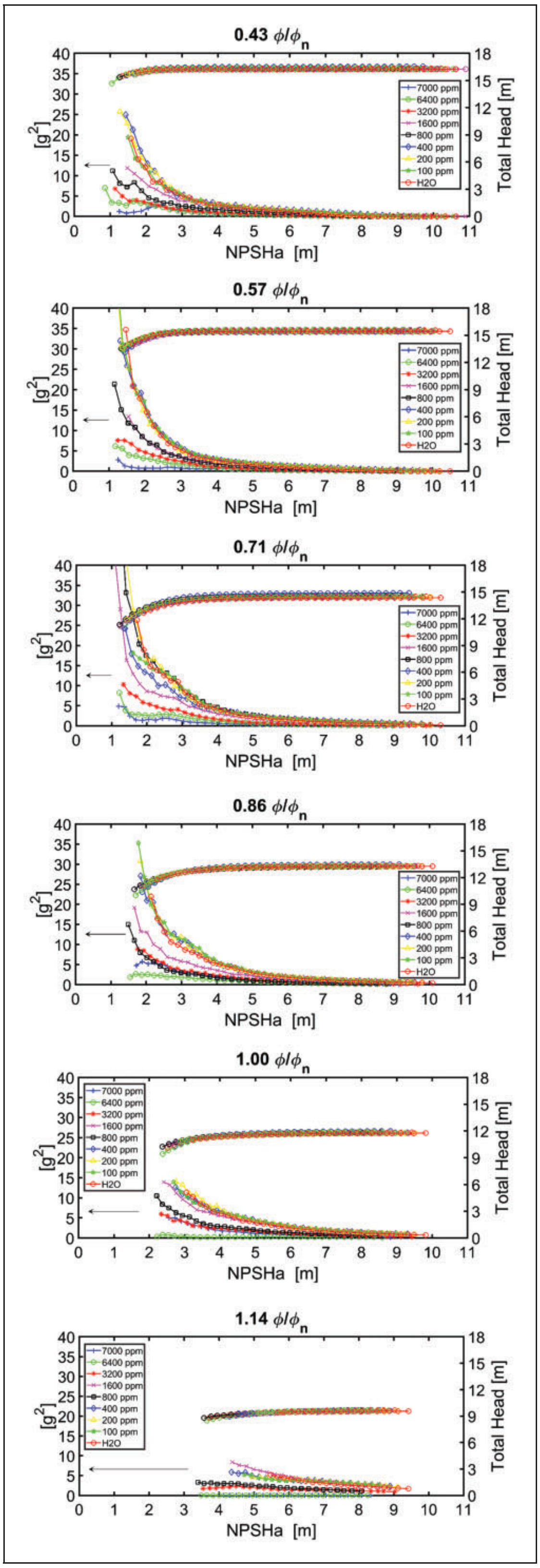

Figure 8. MS values, averaged on three repeated tests for every polymer concentration (frequency range 10 to 12.8 kHz, Z-axis).

The diagram of C shows a mean reduction of about 2%, but this result cannot be generalized due to both the relatively small amount of data obtained so far and the little literature information regarding the variation of NPSHr at different polymers concentrations found by the authors.

Influence of polymers on pump vibrations induced by cavitation

Vibration tests with Polyox WSR 301 have been performed three times for every concentration.

Figure 8 reports the MS values, averaged on the three tests, considering only the frequency range from 10 to 12.8 kHz and the Z-axis, according to the conclusions of paragraph 3.

Generally, the intensity of vibration signals increases with the decrease of NPSHa but, as reported in the literature, an addition of polymers in the solution leads to lower noise generated by cavitation.

These results can be considered in agreement with the literature. In Brujan,[32] it is shown that only the very small cavitation bubbles (with a maximum radius on the order of micrometers) are affected by the polymer additives. The final stage of the collapse phase of the bubble is strongly attenuated and a reduction of the maximum pressure of the emitted shock wave was observed. In literature[7–9] it is reported that a small quantity of polymers additives suppress inception and growth of cavitation, changes the shape of the cavitation bubbles and decreases the energy of the shock pressures drastically. In fact, as explained in Brujan,[10] the collapse of the bubbles in the solution releases less impulsive force compared to water, due to the incremented resistance to extensional flow, with positive effects on cavitation erosion. Tests on different polymer solutions in a cavitation test rig have shown that the weight loss due to the erosion of the sample exposed to a 1% solution presented one order of magnitude less damage than those exposed to pure water.[10] Furthermore, in literature[7,10] the authors explain that the cavitation threshold and erosion effects are affected by the decreased nuclei population, observed with increasing polymer concentration.

Conclusions

Some useful practical information has resulted from this experimental study on the working conditions of small centrifugal pumps used in professional appliances, which process different solutions of polymer dissolved in water. Typically, polymers are substances present in the list of ingredients of detergents of professional appliances.

The behavior of pump total head, absorbed power and cavitation have been analyzed, finding an overall consistency with data found in the open scientific literature. Polymers lead to a minor improvement of total head and a slight reduction of absorbed power because they affect the pump internal losses. The cavitation margin results to be slightly improved with respect to pure water, even if the relatively small amount of data obtained so far will require further analyses.

The most interesting results have been obtained in conditions of incipient cavitation, analyzing the vibration data acquired on the volute case of the pump. These data have been processed to analyze the energy level of the signal at high frequency ranges. It has been demonstrated that, by analyzing the trend of MS with decreasing values of NPSHa the early detection of incipient cavitation is possible, before the typical reduction of total head, avoiding the risk of operating in severe erosion conditions. The amplitude of the vibrations, and the value of the correlated statistical parameters, increase with the decreasing of the polymer concentration. These results are consistent with the literature ones, which show that polymers decrease drastically the energy of the shock pressures and mitigates cavitation damage.

This research will be the foundation for the study of control systems and algorithms in order to avoid the prolonged operating of the pump in unsafe conditions.

Declaration of conflicting interests

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ORCID iD

Fabio Burlon https://orcid.org/0000-0002-0920-9885

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Appendix

Notation

BEP	best efficiency point
c	concentration (ppm)
c^*	overlap concentration (ppm)
C	relative increment of NPSHr with c (%)
e	Euler's number
$E[\,]$	expected value of a random variable
f	Frequency (Hz)
F	forward Fourier Transform
g	gravitational acceleration (m/s^2)
H	relative increment of H_T with c (%)
H_T	total head (m)
I	current (A)
j	imaginary number ($\sqrt{-1}$)
MHP	maximum head point
MS	mean square
$NPSH_{a,r}$	net positive suction head available, required (m)
P	relative increment of power with c (%)
p_v	vapour pressure (bar)
p_s	pressure at pump suction (bar)
Q	fluid flow (m^3/s)
$R_{\alpha\alpha}$	autocorrelation
RMS	root mean square
$S_{\alpha\alpha}$	power spectral density function
t	time
$u_{s,d}$	fluid velocity at pump suction, delivery (m/s)
V	tension *(V)*
α, β	random variable
Δz	height difference (delivery-suction) (m)
Δp	pressure difference (delivery-suction) (bar)
η_s	pure solvent viscosity (Pa s)
$\eta_{sp,0}$	specific viscosity (–)
η_T	total efficiency (–)
η_0	polymer solution viscosity (Pa s)
ρ	density (kg/m^3)
τ	time lag
$\varnothing, \varnothing_n$	flow coefficient $Q/\omega D^3$ with ω (rad/s) angular speed, D (m) impeller diameter and n stands for nominal