



71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16
September 2016, Turin, Italy

Cavitation Detection and Prevention in Professional Warewashing Machines

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Abstract

Cavitation is a phenomenon characterised by the presence of vapour bubbles in the fluid led by a local drop in pressure. In literature it is well known the impact on cavitation of pressure and temperature of pure water, but there are only few studies analysing how the presence of certain components of detergents and additives can influence the phenomenon. The impact of detergents and additives could be explained by the modified viscosity and rheology of the solution but also by the variation in the vapour tension. Most of these effects are due to the presence of surfactants and polymers in the solution. Cavitation in dynamic pumps is an important aspect that needs to be monitored and prevented, because it can cause damages affecting pump performances and inducing an increment in the level of vibration and noise. In professional warewashing machines, as for example the models of Electrolux Rack Type, this phenomenon can affect the operating functionalities of the machine. An experimental pump test rig has been realized with the aim of studying and monitoring the influence of these parameters on cavitation inception. This test rig permits measuring the pump performances at various operating conditions, in order to obtain its characteristic curves, and also forcing cavitation to measure its Net Positive Suction Head required (NPSHr) at different flow rates. The pump test rig allows also testing various configurations of the pump at different cavitation conditions, obtained by changing not only the suction pressure and temperature of the fluid but also its properties, adding detergents and additives. Cavitation inception can be detected measuring both the corresponding prevalence decrease and the change of vibration and noise level.

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Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Cavitation ; Detergents ; Polymers; Professional warewashing machines;

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1. Introduction

In the hydraulic circuit of a warewashing machine, fluid flow circulation and the kinetic energy needed for the soil removal are supplied by a centrifugal pump. The fluid is a solution of detergents and water, and the cleaning process is performed in three main steps. The first step is based on a physical process and chemical reactions that aim to displace the soil from the substrate. A second phase has the function of dispersing the soil into the cleaning medium. The last phase aims to prevent the soil re-deposition. The cleaning process is then guided by four main factors that are chemistry, mechanics, temperature and time. These factors and their interactions are visible in the Sinner's circle [1]. The actual trend in professional appliances is to reduce the time needed for cleaning process, with short washing cycles conducted at low temperatures [2]. This requires a concentrated chemistry for having good washing performance, and high concentrated chemistry could impact also on pump performance, especially on cavitation. A cleaning product is characterized by different components as surfactants, alkalis, acids, builders and other substances. Basically the detergent action in warewashing machines is made by the action of the builders and surfactants. Surfactants, builders and other detergent components could affect the water-detergent solution properties in such a way that it can also no longer be considered a Newtonian fluid, like pure water [3], [4]. These can have an influence particularly on the cavitation inception [5], but in literature there are only few studies on cavitation with detergent solutions, [6], [7], [8], [9], [5], [10], [11]. The present work presents first a literature research on the main parameters affecting cavitation inception which are modified due to detergents components. The wide range of variables affecting the phenomenon has then pushed the necessity to realize a test rig that permits to study cavitation in centrifugal pumps at the different operating conditions and with the detergents used in the professional warewashing sector. The test rig allows to change all possible parameters that can affect cavitation and to test different fluid solutions.

Nomenclature

p_k	Pressure, k stands for undisturbed liquid at distance of the object (0), critical (c), vapour (v);
p_{tk}	Threshold pressure amplitude, k stands for oscillation (v), for a nucleus to grow by rectified diffusion (d);
p_A^k	Vapour tension, k stands for partial of the solvent (p), pure solvent (ps);
v_0	Relative velocity between immersed object and surrounding liquid;
C_k	Concentration of gas, k stands for actual (∞), saturation (0);
S	Surface tension;
$NPSH_k$	Net Positive Suction Head, k stands for available (a); required (r);
ρ	Density of the liquid;
σ_i	Incipient cavitation number;
R_k	Radius, k stands for bubble (b), initial bubble (n);
p_{l0}	Ambient or mean liquid pressure;
x_A	Molar fraction of the solvent;
m_k	Moles, k stands for water (H_2O), potassium caprate (PC);
MM_{PC}	Molar mass of potassium caprate (PC);
w_{PC}	Weight of potassium caprate (PC);

2. Brief analysis of cavitation inception phenomena

Cavitation inception happens when bubbles appears in the fluid flow. Tab 1 classifies hydrodynamic cavitation cases according to [5].

Table 1. Classification of hydrodynamic cavitation

	Characteristics	Zones
Travelling cavitation	Individual transient bubbles which expand and shrink. When bubbles enter in a region of high pressure they collapse.	Bubbles appear in low pressure zones along solid boundaries, or in moving vortices.
Fixed cavitation	Develops after inception. Flow detaches from the rigid boundary of an immersed body or a flow passage.	Bubbles appear in highly turbulent surfaces, in particular in the low pressure side of the blades.
Vortex cavitation	Bubbles form in low pressure cores of vortex regions of high shear.	Bubbles appear in open and ducted propellers.

Considering the relative flow of an object immersed in a fluid, cavitation inception can be reached by lowering the values of local pressure on the surface of the object until a critical pressure p_c . If the surface tension of the bubble is neglected, p_c is also the value of the pressure inside the bubble [5], equal to vapor pressure p_v . An index of dynamic similarity in such condition is the incipient cavitation number, Eq. 1, where p_o and v_o are pressure and relative velocity of the undisturbed liquid at some distance of the object.

$$\sigma_i = \frac{p_o - p_c}{0.5 \rho v_o^2} \quad (1)$$

While the incipient cavitation number is obtained decreasing the pressure until cavitation inception is achieved, a similar index, known as the desinent cavitation number, is obtained increasing the pressure from a cavitation situation until no cavitation is reached. These numbers are not always equal [5]. Cavitation inception and development are strictly related to the bubble dynamics that is associated with the number, distributions and size of gaseous weak spots in the liquid, called nuclei, which dimensions can range from few micrometers to some hundreds of micrometer. Free, or undissolved, gases can act as cavitation nuclei while the dissolved gas content affects their number, size and growth [5]. A free nucleus can be considered to be a spherical bubble, containing vapor and some permanent gas, which stability condition is given by Eq.2 [12], where S is the surface tension and R_b the bubble radius.

$$p_v - p_c = 4S/3R_b \quad (2)$$

Eq.2 shows that the critical pressure for cavitation inception, if the surface tension is taken into account, is less than the vapor pressure but approach it for sufficiently large values of R_b [12]. Considering a pressure field that is constituted by a local mean pressure component p_{l0} and a time varying component, it is possible to calculate with Eq. 3 [12] the threshold amplitude of the pressure oscillation, p_{tv} , needed for a nucleus of an initial radius R_n to grow, according to a vaporous growth mechanism, up to the critical radius at which nuclei become unstable.

$$p_{tv} = p_{l0} - p_v + \frac{4S}{3\sqrt{3}R_n} \left[1 + (p_{l0} - p_v) \frac{R_n}{2S} \right] \quad (3)$$

Another mechanism responsible for bubble growth in time varying pressure fields is gas diffusion, also called rectified diffusion [13]. If there is an oscillation in the ambient pressure, when the bubble is larger than its mean size gas in the solution tends to enter, due to the reduction of its partial pressure in the bubble. On the contrary, gas tends to dissolve when the bubble size is smaller than its mean size. The influx of gas is usually higher than the efflux, so that the bubble tends to increase. This is due to the fact that when the bubble is larger there is a thinner and stretched diffusion boundary layer, with respect to the smaller bubble phase, but there is also a higher surface area [13]. The result is that a small bubble in the fluid under a steady pressure field can disappear but in case of an unsteady pressure field it can grow due to the rectified diffusion. Eq.4 [12], where C_∞ is the actual concentration of the gas, permits to calculate the threshold pressure amplitude, p_{td} , needed for a nucleus to growth by rectified diffusion. This threshold pressure can be an order of magnitude smaller than that for vaporous cavitation for nuclei greater than 1 μm .

$$p_{td} = \frac{\sqrt{2}}{3} p_{l0} \left[1 + \frac{2S}{R_n p_{l0}} - \frac{C_\infty}{C_0} \right]^{0.5} \quad (4)$$

Another parameter that influences cavitation inception is fluid viscosity. It affects the flow turbulence level that determines, in particular, the development of boundary layer and all the related viscous effects. As a matter of fact, cavitation inception occurs mostly in this region, where laminar flow separations and local turbulent transitions are locations of high pressure fluctuations. So nuclei size modifications can occur through mass transfer, as previously discussed, depending also on residence time, which is also affected by viscosity. In [12] the effect of possible different trajectories of a bubble in a boundary layer are described in order to discuss the effects of different pressure fields and residence times on bubble evolution. A bubble involved in boundary layer transition has more residence time in a low and unsteady pressure field. If it goes through a short laminar separation region, the bubble is subjected to a more complex pressure field, characterized by a steady value followed by pressure oscillations in the reattachment zone. A bubble entering in a recirculation region and then into the reattachment zone is subjected to an intermittent steady pressure near the separation region, and an unsteady pressure near reattachment.

In professional appliances, detergents could change viscosity, vapor pressure and rheology of the solution due to their contents of polymers, surfactants and other substances described in the next paragraph. As a consequence, detergents play a significant and hardly predictable role in the cavitation inception behavior of the pump. Experimental analysis is so necessary to underline the influences of warewashing detergents on cavitation inception in the real operating conditions of professional appliances pump.

3. Warewashing detergent characteristics

Detergents used for professional cleaning processes need a stronger and more active formulation with respect to those used in domestic appliances, because less contact time between soil and detergent solutions is required to reach a certain cleaning aspect. They are available as liquid (50 %) or solid block, powder and gel (other 50 %) and are highly alkaline to obtain a good efficiency of soil removal. A mean quantity of detergent used in a wash cycle of the Rack Type is 2 g/l. The forms of energy involved in a warewashing process [2] are presented in Tab. 2.

Table 2. Classification of the energies involved in a warewashing process

Energy	Vector	Details
Mechanical (kinetic energy)	Spray arm nozzles	Water flux and pressure influence the quantity of soil removed from the substrate.
Thermal energy	Hot water	High temperature influences the chemical hydrolysis and the subsequent soil removed from the substrate.
Chemical energy	Detergent chemistry	Soils (proteinaceous, fatty soils, colored stains) are denatured and degraded by the action of detergents combined with the thermal energy in a way that they can be then removed and washed.

High performance detergent contains high concentrations of sodium hydroxide and phosphate builders [2]. In Tab. 3 is presented a general formulation guide and the range of concentration of the various detergent components.

Table 3. General warewashing detergent formulation [2]

Components	Functions	Concentrations
Builder	Sequestration, soil suspension, alkalinity, emulsification, soil peptization.	10 – 20 %
Caustic alkali	Alkalinity, soil hydrolysis, soil removal.	10 – 50 %
Surfactant	Wetting agent, soil removal, spot-film prevention, sheeting action, soil dispersion, drying aid.	0 – 3%
Silicate (optional)	Anticorrosion, alkalinity, soil hydrolysis, soil removal sequestration.	0 – 20 %
Bleach (optional)	Soil removal, stain removal, sanitation, disinfection.	0 – 3%
Defoamer (optional)	Foam prevention, washing efficiency.	0 – 1 %
Thickener (optional)	Product stability, aesthetic enhancement, binder (for liquid product).	0 – 2 %
Color – perfume	Aesthetic enhancement.	< 0.5 %
Water (optional)	Solvent, carrier, flow property.	Balance

Builders provide high and rapid sequestration of water hardness permitting an efficient cleaning process. They avoid that hard water metal ions form insoluble systems with soils, surfactants and detergent materials. Common builders, as Sodium Tripolyphosphate or Silicate, are multifunctional cleaning agents that are also able of powering the surface activity of surfactants. Thus they operate as dispersing and buffering agents suspending the soil and preventing its redistribution. Silicate adds also corrosion protection. There are even polymers secondary builders, as the polyacrylates, which reduce also the crystal growth of calcium precipitate.

Surfactants in warewashing detergents are used at low concentration, especially in mechanical dishwashers. In liquid detergents for warewashing machines it is preferred to use low foaming NI (non-ionic) surfactants, because the foam generated from protein soil and surfactant can cause a drop in water pressure, so decreasing the speed of the spray arm rotor, if any, with consequences on the cleaning effectiveness. Common not foaming substances are polyethylene glycols, fatty acid alkanolamide and EO/PO (Ethylene Oxide / Propylene Oxide) block polymeric surfactants.

Bleach and oxidizing agents are used for remove oxydable food stains coming from vegetables, wine and colour food. Liquid gel or slurry detergents contain thickeners [2].

4. How detergents/polymers components impact on viscosity based effects of cavitation

Detergents cover the entire spectrum of viscosity from low viscosity Newtonian fluids to semisolid pastes [4]. Moreover, the surface layer of a detergent solution may have mechanical properties different from those of the solution itself [3]. This impacts on the stability of foams, because highly stable foams present higher surface viscosity than not stable foams [3]. The desired viscosity and aesthetic formulation in detergents is guaranteed with some appropriate rheology modifiers [4]. In automatic warewashing machines, the most commonly used rheology modifiers are carbomer and cross-polymers, having a high degree of pseudo plasticity [4]. Also surfactants, which are present in particular in all liquid detergents, can alter the solution properties. Considering a neat surfactant solution, at low concentration it has low viscosity and is approximately Newtonian, but if the concentration of surfactants is high, the solution tends to diverge from the Newtonian behaviour [4]. A few analyses on the viscosity of some detergents solutions are presented in [14], [15] and [16]. In details, the viscosity behaviour of a cationic detergent (tetradecyltrimethylammonium chloride) in water and those of various sodium chloride solutions are presented in [14] and reported in Fig.1 (a). The viscosity behaviours of aqueous solutions of three ionic detergents (potassium caprate, sodium oleate and dodecylamine hydrochloride) are described in [15] and represented in Fig.1 (b). From both Fig.1 (a) and (b) it is possible to highlight the increasing trend of the viscosity with the solute's concentration.

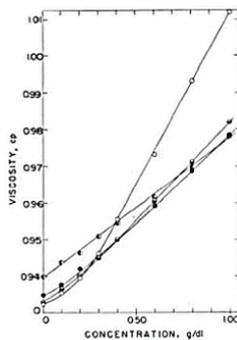


Fig.1 (a) Viscosity behaviour of tetradecyltrimethylammonium chloride in water and various chloride solutions [14]

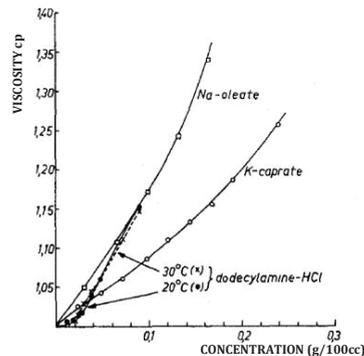


Fig.1 (b) viscosity behaviour of three different aqueous solutions of ionic detergents [15]

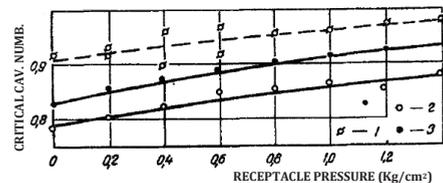


Fig.1 (c) critical cavitation number versus pressure in the tank for 1) water ; 2) 0,1% Polyox WSR-301; 3) Butyl alcohol [6]

The wide rheological spectrum of a liquid detergent therefore requires to examine the water-detergent solution behaviour (Newtonian / Non Newtonian). In literature there are studies highlighting that many polymer solutions are characterised to be Non Newtonian and they have particular effects on the flow as drag reduction, pressure drop reduction and vortex inhibition [5]. In detergents, particularly on warewashing ones, polymers are usually present: Tab.4 shows the characteristic components used in a high alkaline block detergent [2]. For each component, it is highlighted if it is a polymer. In cavitation literature various studies are presented on the effects of polymers addition in water, aiming to study the influence of polymer on cavitation inception [5], [6], [8] [9] [10] [17]. The effects of a polymer solution concentration in different cavitation conditions as jet cavitation, vortex cavitation and cavitation around blunt bodies are presented in [5]. Consider for example a jet cavitation, which occurs in constriction elements as orifices and nozzles. When static pressure is reduced to a critical value there is an increase in the nuclei formation, but a very small amount of polymers additives (diluted solution of flexible polymers, possessing very high values of extensional viscosity) is able to suppress the inception of cavitation. Polymers additives can also affect the cavitation noise, in particular decreasing the time averaged shock pressure [5]. A similar research is presented in [6] where experiments with a hydrophone placed in a pulsed cavitation equipment are described. The author studies the effect of polymer additives (Polyox WSR-301 used in soaps): cavitation number diminishes of 15% with a 0.1% polyox solution, and of 8% with a 0.47% butyl alcohol solution. This behaviour of the cavitation number is represented in Fig.1 (c). Other studies presented in [6] show that surface active agents impact on cavity formation and can reduce the cavitation noise, lengthen the time before inception and decline the

erosion. In [9] it is shown that there is an increased cavitation threshold and a reduced incidence of damage with an increasing amount of polymer additives. The mechanism of cavitation suppression by polymer additives is discussed in [5]. It is not completely understood but, in the case of cavitation around blunt bodies, it is due to an earlier transition to turbulence that suppresses the laminar separation region, where cavitation usually happens. Instead, in tip vortex cavitation, the ejection of polymer from the wing tip reduces the tangential velocity by increasing the pressure in the core of the vortex, thus retarding the cavitation inception. In [8] authors investigate the role of polymers on the delay of tip vortex cavitation. Polymers increase tip vortex core radius delaying and lowering cavitation inception. In vortex chamber with polymer solution, the delay of cavitation inception seems to be due to an increased turbulent kinetic energy rather than to a growth of the viscous core or to a decreased rotational speed [10]. A homogeneous polymer solution suppresses cavitation in foils acting on tangential velocities thus modifying circulation and lift [5]. Some polymers in viscoelastic fluids suppress cavitation inception by affecting extensional viscosity, lowering the speed of the solution and increasing resistance and static pressure [5].

Table 4. High alkaline warewashing block detergent compositions - US Patent 4846993 [2]

Ingredients	Type of component	Polymer	Phosphate	Nonphosphate
Water			3 – 10 %	8 – 15 %
Sodium hydroxide (50%)	Inorganic compound	No	7 – 20 %	7 – 20 %
Sodium polyacrylate (50%)	Anionic polyelectrolyte with negatively charged carboxylic groups in the main chain	Yes	8 – 20 %	2 – 6 %
Phosphino polycarboxylate Desquet 2010	Anionic polymers	Yes	-	-
Nonionic surfactant	E.g. Polyethylene glycol. Forms: oligomer or polymer of ethylene oxide.	Yes	1.5 – 3	1.5 – 3
Sodium hydroxide bead	Inorganic compound	No	40 – 45	40 – 45
Sodium sulphate	Inorganic compound	No	5 – 10	5 – 10
Sodium chloride	Inorganic compound	No	3 – 6	3 – 6
Sodium tripolyphosphate	Inorganic compound	No	30 – 45	-
Phosphate ester defoamer	Deaerating wetting agents	No	0.2	0.2
Solid chloride bleach source	Salt of hypochlorous acid	No	7.5	7.5

5. Surfactants impact

When a bubble is placed in an oscillating pressure field, rectified mass diffusion can occur, as seen in introduction [12] [18] [19]. Surfactants influence rectified diffusion [7] [11]. Surfactants are present in detergents and tend to form aggregates such as micelles [20], constituted by a hydrophilic head directed through the water interface and a hydrophobic tail directed through inside and attracted by the soil. The main properties and actions of the surface active agents are wetting, emulsifying, peeling and foaming actions. The bubble growth rate is enhanced by the action of the surfactants due to their impact on surface tension, interfacial resistance to mass transfer and surface rheological properties. An effective plot of these effects is reported in Fig.2 [7] where it is possible to see the variation in bubble radius and growth rate. In Fig.2 (b) the initial bubble radius is 25 μm and is smaller than the threshold bubble radius for rectified diffusion that is 32 μm at 0.22 bar and 22.1 kHz [7]. In Fig.2 (a) it is shown that the size of a bubble of initial radius 20 μm remains constant over 300 s and then it dissolves.

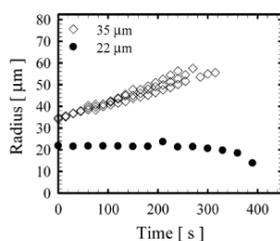


Fig. 2 (a): Variation of bubble radius as a function of time in air saturated water [7]

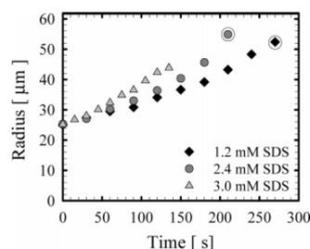


Fig. 2 (b): Variation of bubble radius as a function of time for different bulk concentrations of SDS [7]

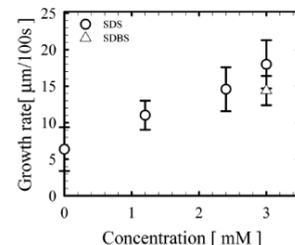


Fig. 2 (c): Bubble growth rate as a function of SDS bulk concentrations [7]

6. How detergents components impact on vapor pressure

Detergents have the property of lowering the surface and interfacial tensions other than solubilising and emulsifying abilities. The trend of the partial vapour tension of the solvent with the addition of solute is related with the thermodynamics of the solution and is given by the Raoult law. The properties of nineteen solutions of detergents at various concentrations are presented in [21]: considering for example potassium soap (potassium caprate) diluted in water, the Raoult law is represented in Eq.5.

$$p_A^p = x_A \cdot p_A^{ps} = \left(\frac{m_{H_2O}}{m_{H_2O} + m_{PC}} \right) \cdot p_A^{ps} \quad (5)$$

Given the molality of the solute, it is possible to obtain the moles of solute, m_{PC} , and the corresponding grams, w_{PC} , with Eq.6 where, for potassium caprate, MM_{PC} is 210.35 g/mol.

$$w_{PC} = MM_{PC} \cdot m_{PC} \quad (6)$$

The grams of solvent are calculated subtracting the grams of solute from one kg of solution, and the subsequent moles of water, m_{H_2O} , are obtained dividing by its molar mass. Applying Eq.5, the resulting variation of the partial vapour tension of water as a function of the molality of potassium caprate solution is obtained at a given temperature, as shown in Fig.3.

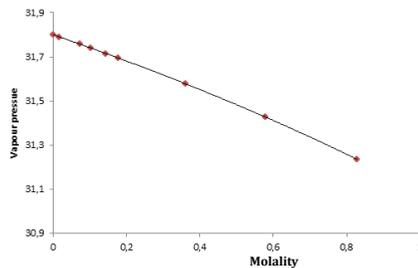


Fig.3.: Calculated partial vapour pressure (in mmHg) vs. molality of water - potassium caprate solutions at 30°C, based on the data presented in [21]



Fig.4.: Test rig

7. Plant characteristics

A test rig has been designed according to the International Standard 9906:2012 [22]. It permits to measure the characteristic curves and NPSHr of different pumps, as in [23], [24], with various fluids (water - detergent solutions at different concentrations). In the NPSH_r test the NPSH_a is progressively reduced by changing the pressure of the free surface level in the tank or the temperature of the fluid (acting on the vapour pressure of the fluid), until there is a 3% prevalence/power decrease at a certain fluid flow [23], [22]. The pump is installed in a closed circuit where the main pipes have external diameter DN 65. The tank is designed to avoid inclusions of gases in the suction of the pump. Inside the tank are installed two electric resistances (one of 17 kW and the other of 9 kW), two calm screens, a spray nozzle device and a vacuum inlet for controlling the pressure on the free surface. At the bottom and top of the tank are installed two valves. Pressure transducers are positioned at a distance of two diameters from suction and outlet section of the pump and they are provided by Trafag (power supply 24 V-DC; signal output 10 V-DC; precision 0.15% on full scale). An accurate measure of the fluid flow is reached positioning the flow meter at ten diameters from the pipe curve and five diameters from the branch connecting the deaeration nozzle. The flow meter is provided by Endress Hauser (power supply 230 V-AC; output signal 4-20mA; error 0.5% on the read value). The pump has a twelve diameters length straight pipe at the suction, for reaching a uniform velocity and pressure distribution. Fig.4 presents a picture of the test rig. Cavitation is the cause of structural vibrations, which will be detected at the beginning of the cavitation process (inception) with a microphone and accelerometers. Vibrations are acquired by three accelerometers ICB Piezoelectric (sensitivity 100 mV/g; range: -50g to 50g). To characterise their components along three axial directions, the optimal positions of the sensors in the volute pump will be determined

with preliminary tests. Pressure sound is measured by means of a ICB Piezoelectric sensor (sensitivity 39.2mV/Pa in the range from 0 to 120 dB). For monitoring different operating conditions of the pumps and to find the correlation between accelerometers signals and power a Yokogawa digital power meter (accuracy 0.1% in reading) is used to check current-voltage-power supply values. Furthermore, a type K thermocouple is used for monitoring the resistance temperature and a Pt100 for measuring the solution temperature in the tank.

8. Conclusions

The article presents a literature review on some physical phenomena and parameters involved in the inception and development of cavitation. In particular, it focuses on the main flow properties that can be affected by the use of detergent solutions as pumped fluid. From the literature research it appears that there are only few studies relating cavitation inception in the presence of liquid detergents. They could affect cavitation due to the content of surfactants - polymers and other components in the solution, which could alter rheology, surface tension, viscosity and vapor pressure with respect to the case of pure water. It emerges that surfactants enhance the bubble growth rate, impacting on rectified diffusion and polymers decrease the incipient cavitation number. Finally, the paper describes the test rig realized to analyze the phenomenon in the real operating conditions of professional warewashing pumps. The next steps of the research will be the conduction of experimental test on cavitation inception and development in different pumps, using water and detergent solutions at various concentrations and temperatures. The measurements will regard the overall performance of the machines, the determination of the NPSHr curve and the characterization of vibrations and noise.

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