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Determination of the Tensile Strength and the Nuclei Concentration by Means of the In-Situ-Nozzle

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ABSTRACT

In this paper a new method for the determination of the tensile strength in combination with the underlying distribution of free cavitation nuclei is presented. This method is based on the advancement of the in-situ-measuring of the tensile strength by means of the so-called “in-situ-nozzle” originally presented at the CAV2006 Symposium [11]. The in-situ-nozzle works as a cavitation susceptibility meter that is based on the venturi principle [8]. In contrast to several previously presented cavitation susceptibility meters the in-situ-nozzle can be used to measure the tensile strength “in-situ” i.e. directly within a hydraulic pipe, without the need for any bypass connections. Consequently the in-situ-nozzle serves as a measuring device for the detection of the tensile strength at basically any position within a hydraulic circuit. The adjacent analysis method that has been developed to evaluate the collected data allows for providing additional information on the freely distributed cavitation nuclei in an operating test installation. For this purpose the measured tensile strength is associated with the critical size of gas bubbles acting as cavitation nuclei. Following this approach it is possible to give an approximation of the currently existing nuclei size distribution respectively the nuclei concentration at the mounting position of the in-situ-nozzle. By installing two identically constructed in-situ-nozzles in a centrifugal pump test rig the tensile strength and the nuclei concentration at two positions with different boundary conditions are determined. One nozzle is mounted directly upstream of the test pump, whereas the other one is installed in

the pressure pipe downstream of the pump. This is done first of all, to examine the capability of the measuring device of being sensitive enough for a change in the boundary conditions in general. If this is verified, the two nozzles can be adopted to particularly investigate the influence of specifically chosen operating points of the test pump on the tensile strength as well as on the underlying nuclei concentration.

INTRODUCTION

It is well known that freely distributed particles within a liquid serve as nuclei for bubble cavitation. Mostly these particles are small gas bubbles, frequently also termed nuclei, with a typical size range of a few microns up to a couple of hundred microns (see e.g. [3]). They act as cavitation seeds at which the evaporation of the surrounding liquid can occur. In a pure liquid where no nuclei are present at all, the minimum pressure to which the fluid could be exposed to without the occurrence of cavitation theoretically would tend to very high negative values [3], since the sites for evaporation to start at would be missing. Thus Briggs for example managed to measure tensile strengths of up to several hundred bars [4]. The actual value of the tensile strength of the liquid i.e. the difference between the thermodynamic vapour pressure and the static pressure provides a measure to quantify the tendency of the liquid with regard to cavitation inception.

As in most of the cases the cavitation nuclei are formed by gas existing in the surrounding liquid, the gas content of the liquid plays an essential role for the formation of the nuclei size

distribution. Thus in the course of experimental investigations on cavitation it should always be measured as well. Concerning water, this content of dissolved gas, which will predominantly be air and the tensile strength are often summarized and then referred to as the water quality.

The onset of cavitation in a centrifugal pump as well as its head drop behaviour strongly depends on the contemplated properties of the fluid. Hence there is a great demand for a consistent way of also quantifying the water quality in a hydraulic installation, in order to obtain reliable information on the probability for the occurrence of cavitation at certain operating points. Moreover a standardised method for the determination of the water quality would form a convenient way to properly compare the state of the water with respect to cavitation in different hydraulic installations. This also includes the assignment of the fluid properties in a test rig to the subsequent operating conditions in the real hydraulic installation. With the in-situ-nozzle along with the adjacent evaluation process and in combination with a simultaneous indication of the content of the dissolved air a new measuring device for assigning the water quality in an operating pump test rig is introduced.

EXPERIMENTAL SET UP

The set up for the experimental investigations consists of the in-situ-nozzle system including two in-situ-nozzles and a closed loop centrifugal pump test rig. A schematic of the complete test installation is shown in figure 1. The explicit setup and functionality of the subsystems are described in detail within this section.

Test rig installations

The test rig can be operated in two loop configurations in order to change the fluid volume and hence the residence time. The total volume including the respective separation tank (B001 and B002 in figure 1) and pipe arrangement is approximately 8.8 m³ for the long circuit and about 2 m³ for the short circuit. That yields to a mean residence time of about 4 minutes for the long circuit and 32 seconds for the short circuit, both referred to the optimal operating point of the test pump.

The radial centrifugal pump has a specific speed of

$$n_s = n \frac{Q_{opt}^{1/2}}{H_{opt}^{3/4}} = 26 \text{ min}^{-1} \Rightarrow n_{s,USA} = 1384 \text{ rpm} . \quad (1)$$

At its optimal operating point and when actuated with water it delivers a hydraulic head of 28 m at a flow rate of 125 m³/h and a rotational frequency of 1750 rpm. For the purpose of cavitation observations within the blade channels the front panel of the impeller as well as the upstream section of the suction pipe are made of acrylic glass and will be subsequently referred to as the visibility section. As illustrated in figure 1 the two loops of the test rig share one pressure pipe that includes two separate throttle valves, both of which can be used to adjust the flow rate (positions 3 and 4 in figure 1). Furthermore there is a mobile vacuum pump available that can be easily attached

to the separation tank of the circuit currently in operation, in order to regulate the value of

$$NPSHA = \frac{p_{tot,1} - p_v(T_\infty)}{\rho g} \quad (2)$$

at the suction side of the test pump.

The pressure gauges for the calculation of the hydraulic head of the test pump are located at the inlet of the visibility section approximately 4 cross-section dimensions upstream of the pump inlet and in the pump casing respectively. Resulting from a special casing design the velocity at the outflow of the pump cannot be measured and hence the hydraulic head is calculated by

$$H = \frac{p_2 - p_1}{\rho g} \quad (3)$$

in which p_1 and p_2 are the static pressures at the two given locations (positions 1 and 2 in figure 1).

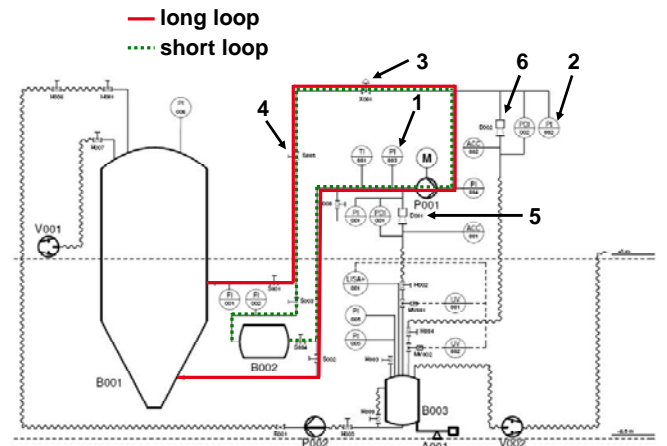


Figure 1: Schematic illustration of the centrifugal pump test installation (positions 1 and 2: pressure gauges for the pump inlet and the pump outlet pressure; positions 3 and 4: throttle valves; positions 5 and 6: in-situ-nozzles mounted in the suction pipe and the pressure pipe)

In-situ-nozzle

The whole system of the in-situ-nozzle is subdivided into the nozzle itself, the suction unit and the controlling software. Advancements of the system within the recent years mainly apply to the suction unit and to adaptations of the controlling software, whereas the construction of the in-situ-nozzle remains nearly unchanged. Apart from that the measuring task of the in-situ-nozzle has been enhanced from merely measuring the cavitation susceptibility to also providing a measure for the underlying nuclei concentration inside an operating test pump installation. In connection with that a second construction of the in-situ-nozzle was manufactured, in order to install two nozzles at different locations of the test rig at the same time. The nozzles itself have identical geometry, only the cross-sections of the suction pipes are slightly different. As it will be seen from the subsequent remarks on the arrangement of the instrumentation respectively the measuring principle, this of

course will not have any effect on the performance or rather the comparability of the two nozzles.

Figure 2 shows the cross-section of the nozzle part and figure 3 illustrates the mounting situation of the in-situ-nozzle within a pipe of circular cross-section. However, due to the fact that the in-situ-nozzle is mounted through a simple borehole it can also be installed inside a pipe of rectangular cross-section without any problems.



Figure 2: Cross-section of the nozzle part of the in-situ-nozzle system

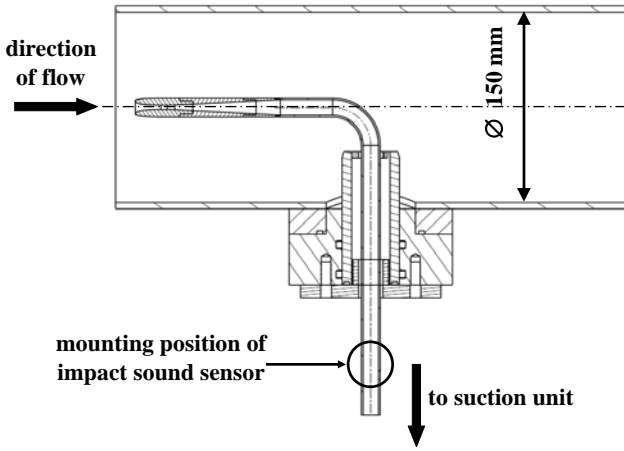


Figure 3: Installation position of the in-situ-nozzle within a pipe of circular cross-section

The suction unit consists of a tank with a volume of about 120 litres, a vacuum pump and two electromagnetic proportional valves identical in construction. The suction pipes of the in-situ-nozzles are each connected to the basin via a flexible tube that includes the particular proportional valve. The tank in turn is connected with the vacuum pump by a tube that is fixed at its top cover. The vacuum tank itself is placed in a shed underneath the test rig so that the alignment of the hose pipes in the cap of the vacuum tank is at a level of approximately 2.2 m below the suction pipe of the test rig. During the preparation phase of the experiments the tank is evacuated by the vacuum pump to an absolute pressure of about 70 mbar. With the objective of providing a nearly constant suction pressure inside the tank, the vacuum pump is kept running during the experiments.

Measuring principle

The measuring of the tensile strength is based on the venturi principle. A flow of liquid is conducted through the in-situ-nozzle and continuously increased until first occurrences of cavitation are obtained in the minimal cross-section. This is detected acoustically by an impact sound sensor attached to the external wall of the suction pipe of the nozzle as indicated in

figure 3. By synchronously determining the static pressure in the minimal cross-section p_{∞} , the tensile strength of the liquid is defined as

$$\Delta p_{crit.} = p_v(T_{\infty}) - p_{crit.\infty}. \quad (4)$$

It is known from numerous investigations that pressure taps in the surface of a solid wall can induce cavitation as they serve as residing places for cavitation nuclei (see e.g. [2]). Hence a hole in the inner wall of the in-situ-nozzle at the cross-section of the minimum static pressure, i.e. the throat of the nozzle, could lead to a greater occurrence of cavitation or move the limit of cavitation inception to a higher pressure. Since this would inevitably lead to a detection of smaller values of the tensile strength, the pressure in the minimal cross-section cannot be determined in this kind of way. Consequently it is necessary to ascertain this pressure in an indirect manner. Thus the static pressure is measured in the diffuser of the nozzle where it is backward above the vapour pressure again and hence an influence on the measuring result through the pressure gauge itself is highly improbable. The required pressure in the nozzle throat is then obtained by a backward calculation that is based on the correlation between the pressure in the minimal cross-section, the flow rate and the measured pressure in the diffuser, which has been preliminary identified through CFD calculations.

As the extracted volume flow is needed to calculate the static pressure in the minimal cross-section it is automatically incorporated in the determination of the tensile strength through equation (4). That means any fluctuations in the signal representing the flow rate might have a significant effect on the results obtained. Thus it is essential to assign the flow rate with the highest accuracy accessible to account for the dynamics resulting from the continuous increase of the extracted flow. This is achieved by determining the flow rate indirectly from the pressure difference between a second gauge in the suction pipe and the gauge in the diffuser of the nozzle. For this purpose the relation between this pressure difference and the flow rate is obtained in a preliminary calibration process. Clearly this correlation is only valid as long as there is no occurrence of advanced cavitation, as that would cause a strong increase in the pressure losses.

The enhanced scope of operation of the in-situ-nozzle as a measuring device not only for tensile strengths but also for the concentration of cavitation nuclei is associated with the assumption that the incidence of the tensile strength is equivalent to the explosive growth of these nuclei. This in turn means that the static pressure of the liquid in the vicinity of such a cavitating nucleus must be low enough for it to become unstable. To evaluate the size of a specific nucleus it is further assumed that the nuclei are always bubbles of spherical shape consisting of both a condensable and a non-condensable gas, namely being the vapour of the surrounding liquid and undissolved air respectively. The equilibrium radius of the bubble is determined by the balance

$$p_{\infty} + \frac{2S}{R_E} = p_v(T_{\infty}) + \frac{3m_g R_g T_{\infty}}{4\pi R_E^3}, \quad (5)$$

where p_∞ is the pressure in the surrounding of the bubble. The left side of (5) is the sum of the partial vapour pressure $p_v(T_\infty)$ and the partial pressure of the air. Transposing equation (5) gives the expression for the subsequent calculation of the equilibrium bubble radius

$$(p_\infty - p_v(T_\infty))R_E^3 + 2S R_E^2 - \frac{3m_g R_g T_\infty}{4\pi} = 0. \quad (6)$$

In order to determine the size of a specific bubble it is necessary to connect the ascertained tensile strength with the bubble radius. This is achieved by defining the incidence of the tensile strength to be the instant at which a bubble of a particular initial size exceeds its critical radius. This is equivalent to the conclusion that the static pressure in the vicinity of the bubble is equal to the critical pressure of the bubble: $p_\infty = p_{crit.\infty}$. By now taking Blake's expression for the tensile strength

$$\Delta p_{crit.} = \frac{2S}{R_{crit.}} \frac{3n-1}{3n} \quad (7)$$

and therein replacing the critical bubble radius with the Blake radius [1]

$$R_{crit.} = \sqrt{\frac{9 n m_g R_g T_\infty}{8 \pi S}} \quad (8)$$

an equation for the calculation of the mass of the bubble subject to the measured tensile strength is obtained.

$$m_g = \frac{32\pi}{9n} \frac{S^3}{\Delta p_{crit.}^2 R_g T_\infty} \left(\frac{3n-1}{3n} \right)^2 \quad (9)$$

Here the polytropic exponent is usually assumed to be one, which implies isothermal behaviour of the air in the bubble and reduces equation (9) to

$$m_g = \frac{64}{81} \frac{S^3}{\Delta p_{crit.}^2 R_g T_\infty} \cdot 2\pi. \quad (10)$$

Beyond this, an approach to account for the time behaviour of the gas inside a cavitation bubble is presented in [9]. Once the bubble mass is known the value of the critical radius can be calculated using equation (8).

With the assumption that the incidence of the tensile strength is ever aroused by a single cavitating bubble/nucleus, the approach described above can be used to identify the size and hence the concentration of cavitation nuclei at the mounting position of the in-situ-nozzle. As the bubbles grow due to the pressure drop between the nozzle inlet and its minimal cross-section, the critical bubble radius associated with a single cavitation event must be calculated back to the initial bubble radius at the inlet of the nozzle. Assuming that mass

diffusion during the residence time inside the nozzle is negligible, it is sufficient to know the static liquid pressure at the inlet of the nozzle rather than knowing the entire pressure history between the inlet and the minimal cross-section. The magnitude of the diffusion time can be estimated with the equation

$$t_D \sim \frac{R_E^2}{D} \quad (11)$$

in which D is the diffusion coefficient due to molecular diffusion of air in water ($\sim 1e^{-9}$ m²/s for room temperature). For a bubble with a typical initial radius of 10 μ m that yields to a diffusion time in the range of 0.1 seconds. Given the typical residence time of a bubble between the inlet and the smallest cross-section of about 4 milliseconds the diffusion time is two orders of magnitude longer than the residence time and hence the assumption of diffusion to be insignificant is appropriate. Apart from that it is intended to refine the model by allowing for diffusion based on a turbulent diffusion coefficient given by G. I. Taylor in the future.

Following the above reasoning, the initial bubble radius at the inlet of the in-situ-nozzle can be calculated with the static equilibrium equation (6) by inserting the static pressure at the nozzle inlet and the bubble mass obtained from equation (9). The whole procedure of attaining the initial bubble radius from the measured tensile strength is demonstrated again in figure 4.

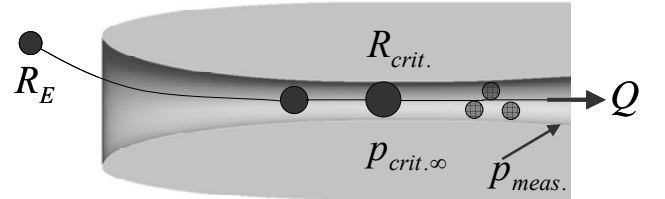


Figure 4: Growth of a cavitation bubble along a path line between the inlet and the throat of the in-situ-nozzle where it becomes unstable.

Experimental Procedure

The above introduced way of determining the size of single cavitation bubbles/nuclei and hence the nuclei concentration requires several specifications on the experimental procedure. Since each single event of cavitation i.e. each single value of the tensile strength is always associated with only one cavitation bubble of a specific minimal radius, it is necessary to deliberately generate as many single cavitation events as possible, in order to assure an appropriate resolution of the actual bubble concentration. Moreover, as the size of the detectable bubbles changes with the extracted volume flow, this needs to be varied in a potentially broad domain to maximize the size range of the measurable nuclei. As a matter of course the applied procedure has to be adapted to several restrictions resulting from the limited capacity of the vacuum tank, the measuring time, the used measuring board and the operating conditions of the test installation, to mention the most important constraints. Therefore the measurements have to be carried out as described in the following. The determination of the actual tensile strength respectively the concentration of the

entire bubble/nuclei size range actually consists of a series of single measurements. In each of these single measurement runs the flow rate is increased between certain limits. These always need to be chosen in a way that the static pressure in the throat of the nozzle certainly drops below the vapour pressure during the measurement interval, for real vapour cavitation to can occur. Therefore at first the limits of the raise of the extracted flow rate are set to adequate values for the initial flow rate to be lower and the final flow rate to be higher than the minimum volume flow rate needed to undercut the vapour pressure in the minimal cross-section. This ensures that the largest nuclei are detected first. This process is repeated several times until sufficient cavitation events have occurred to form a representative average value of the tensile strength and to attain a high enough resolution of this first part of the total nuclei size range. Experience has shown that this is achieved with reasonable accuracy in the most critical cases after five single measurement runs. Subsequently the limits for the increase of the flow rate are shifted to a higher range to account for the smaller nuclei existing at present. This again is repeated just as many times as it has been done for the first range of the volume flow. As the case may be, the procedure is applied to a still higher range of the flow rate, in order to detect even smaller nuclei. However, the necessity for doing so strongly depends on the current operating point of the test rig. By merging all conducted measurement runs of the adjusted volume flow regions the complete nuclei size range is composed. Before exemplifying the exact procedure for this, a typical result of a single measurement run is plotted in figure 5. The displayed time signals show an explicit example of the first range of the extracted volume flow elevation, as the throat pressure at the beginning of the increase is far above the vapour pressure. After about two seconds the throat pressure drops below the vapour pressure and from that time on real cavitation events can occur. The circled intervals of the acoustic signal show the characteristic peaks of these single cavitation events, seven of which can be clearly distinguished here.

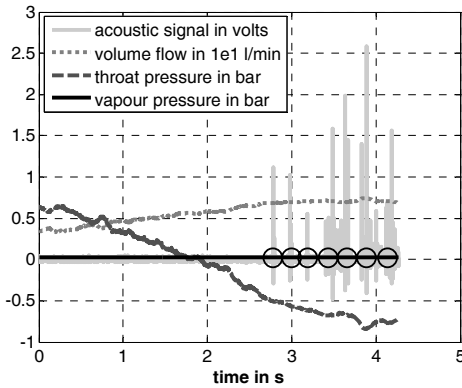


Figure 5: Resulting time signals of a single measurement run (amplified and filtered acoustic signal in volts, flow rate in $1e^1$ l/min, throat pressure and vapour pressure in bar)

The procedure of deriving the nuclei size distribution from a series of measurement as it has been introduced so far is naturally based on the overall assumption that the nuclei concentration does not change in time during the period needed

for the measuring. Furthermore the fluid sample being investigated at a certain time inside the nozzle must be representative for the state of the fluid at the mounting position outside the nozzle. One reason for this is the fact that the tensile strength is subject to a certain variation, which in turn is due to the statistical distribution of the underlying nuclei. This can be seen in figure 6 which shows the calculated values of the tensile strength for a whole series of measurement. The range of the captured values reaches from more than 0.08 MPa to even negative values, which are equivalent to events of pseudo cavitation. In terms of the nuclei these negative values of the tensile strength represent large bubbles that become unstable above the vapour pressure.

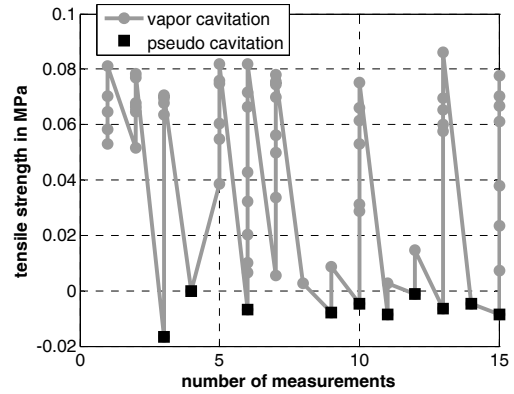


Figure 6: Calculated values of the tensile strength from a series of measurement with a total number of 15 single test runs

The method for the determination of the nuclei size distribution in terms of the bubble concentration at the inlet of the in-situ-nozzle is subdivided into four steps of calculation. The first step consists of the calculation of the tensile strength from the merged set of all single measurement runs belonging to a series of measurement, like it has also been done for the diagram in figure 6. Accordingly the associated bubble radii are calculated as it was described before. Resulting from the continuous increase of the extracted flow rate the bubble radius is a function of this

$$R = f(Q) \Rightarrow R_k = f(Q_k). \quad (12)$$

The radii are chronologically charted in a table which additionally contains the actual number of the measurement run, as well as the point in time with respect to the particular run at which the relative cavitation event was detected, and the underlying value of the tensile strength. This information is needed for the subsequent calculation of the bubble concentration. In the next step the matrix is sorted according to the bubble radius. Then the concentration of each nucleus is calculated with the equation

$$c = \frac{dN}{dV} = \frac{dN}{dt} \frac{dt}{dV} = \frac{dN}{dt} \frac{1}{Q(t)} \Rightarrow c_k \approx \frac{\Delta N}{\Delta V_k} \quad (13)$$

in which the numerator represents the variation of the number of events and the denominator marks the volume that has been extracted through the nozzle since the previous single event

$$\Delta V_k = \int_{t_{k-1}}^{t_k} Q(t) dt \Rightarrow \Delta V_k \approx \frac{Q_k + Q_{k-1}}{2} \Delta t. \quad (14)$$

It is important to note here that due to the measuring principle the variation of the number of events in the numerator always has to be unity. This is with regard to the fact that the acoustic signal does not provide information about the exact location inside the nozzle at which a detected cavitation event has occurred. As a matter of fact a detected event could have occurred at any position between the nozzle inlet and its throat at which the static pressure is low enough for the respective bubble to become unstable. Since the pressure is continuously decreasing between the nozzle inlet and the minimal cross-section, the exact size of the bubble cannot be determined. Consequently by applying the described method of equalizing the static pressure in the nozzle throat with the critical pressure of a currently detected bubble the calculated radius of this bubble always has to be considered as the minimum possible radius. It will be seen from the results presented in the next section that this implies important consequences for the resulting bubble/nuclei concentration. The way of calculating the single concentration values with equations (13) and (14) is pictured schematically in figure 7. It shows a characteristic curve of the continuous increase of the volume flow and five randomly set single events as well as the related bubble radii. In this case only the three numbered dots represent events that can be incorporated in the evaluation process. This is because Q_i denotes the minimum flow rate needed for cavitation inception in the throat of the nozzle and thus the first event of real vapour cavitation is the second one. That again means the first event that can be clearly associated with a single concentration value calculated with equations (13) and (14) is the overall third one.

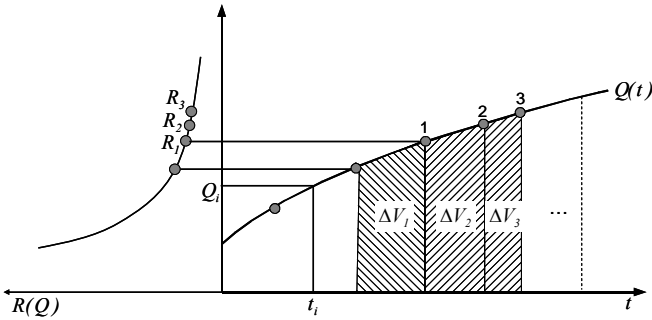


Figure 7: Procedure of calculating the single values of the concentration from the time signal of the extracted volume flow and the detected single events with the associated bubble radii

RESULTS

As it was mentioned in the first section two examples of the in-situ-nozzle are used for the experiments to be able to measure the tensile strength at two different locations within the running test installation. This is done in order to examine mainly two things about the underlying nuclei size distribution.

The first objective is to collect information about the nuclei size distribution at different positions within a hydraulic circuit. This is related to the fact that the bubble radius is a function of the current liquid pressure and hence the bubble size distribution differs between the different line sections of the circuit. The second thing of interest is to obtain further knowledge about the influence of the operating conditions of the test installation on the nuclei size distribution. These two ambitions make different demands on the exact experimental or rather the evaluation procedure in terms of the appropriate pressure with which an obtained nuclei size distribution has to be scaled.

The two measuring positions selected here are the visibility section and the pressure pipe proximately upstream and downstream of the test pump (see positions 5 and 6 in figure 1). If pursuing the first of the above objectives the corresponding static pressures at these locations have to be determined. For the nozzle on the suction side the same gauge as the one taken for the detection of the pump inlet pressure is used (position 1 in figure 1). In contrast to this, due to its exact mounting position the inlet pressure of the in-situ-nozzle on the pressure side is different from the one in the pump casing and hence an additional pressure gauge was installed in the accordant section of the pressure pipe (position 2 in figure 1). In the second case of being primarily interested in the comparison of the nuclei size distributions at the two measuring positions respectively the influence of the operating conditions the reference pressure for the scaling of the bubble radii is taken to be atmospheric pressure.

Operability of the in-situ-nozzle

In order to verify the operability of the in-situ-nozzle as a measuring device that can be used to determine the nuclei size distribution the test rig was always assured to run at steady conditions. For this purpose the test pump was adjusted to its design point and the suction pressure was reduced to a value of about 50% atmospheric pressure. Though this was done to provide the appropriate boundary conditions to get preferably many cavitation events inside the in-situ-nozzle the chosen pressure value excluded the test pump from cavitating itself. Figure 8 shows the resulting nuclei concentration chart of such a test series, which by consisting of 15 single test runs follows the measuring procedure explained in the previous section. As the way of calculating the bubble radius inevitably leads to as many distinct radii as the number of single events that have been detected, it is reasonable to calculate mean values of the concentration by grouping the events in appropriate classes of radii as it is done in figure 8. It can be seen that the size range of the detected bubbles reaches from nearly 200 μm down to a couple of microns and thus the observed nuclei are situated in about the same order of magnitude as it has been variously determined with other measuring techniques (e.g. [7], [10] and figure 9). In addition by dividing the values of the concentration in figure 8 by the typical bubble radius of 10 μm the resulting number density distribution ranges in the same order of magnitude as it was observed by LIU and BRENNEN. However, the concentration values in figure 8 do not increase for a decreasing bubble radius as it is the case when integrating the number density distributions seen in figure 9 with respect to

the bubble radius to obtain the bubble concentrations. One reason for this could be the fact that the usage of the in-situ-nozzle solely accounts for bubbles that act as real cavitation seeds and that all other types of particles do not contribute to the calculated nuclei concentration. In this context it also has to be noted that the content of the dissolved air during the measurements was only about 25 % saturation and hence the nuclei concentration must be expected to be very low. Another possible reason for the ascertained discrepancy is the already alluded blurring of the calculated value of the bubble radius, which can eventually lead to partially wrong allocated values of the concentration. Though these possible causes should be further investigated, for example by deliberately injecting uniformly sized nuclei directly in front of the nozzle inlet, there are also results obtained with other measuring techniques that look quite similar to the one presented in figure 8. Figure 10 for example shows a comparison of the bubble concentration chart from figure 8 with those obtained with the Acoustic Bubble Spectrometer® (ABS) [6] and with Phase Doppler Anemometry. Though the corresponding measurement data was collected in three different test installations the water was similarly conditioned in all three cases. It is seen that both the nuclei size range and the order of magnitude of the concentrations do coincide with each other quite well. Also none of the three concentration charts is monotonically increasing with a decreasing radius.

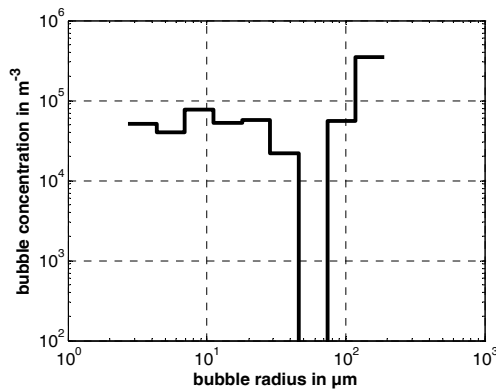


Figure 8: Bubble concentrations on the suction side of the running test pump at 0.45 bar pump/nozzle inlet pressure. This corresponds to an operating point of the test pump free of cavitation. The bubble radii are scaled with a static pressure of 1 bar.

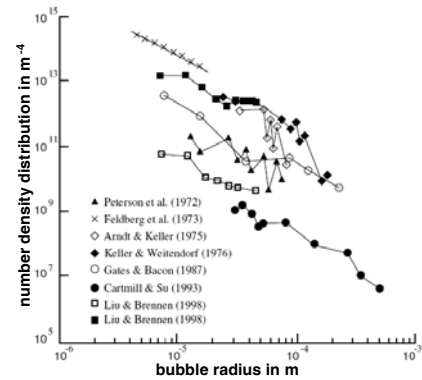


Figure 9: Collection of several number density distributions in variously conditioned water, determined with different measuring techniques (taken from SAUER [11]).

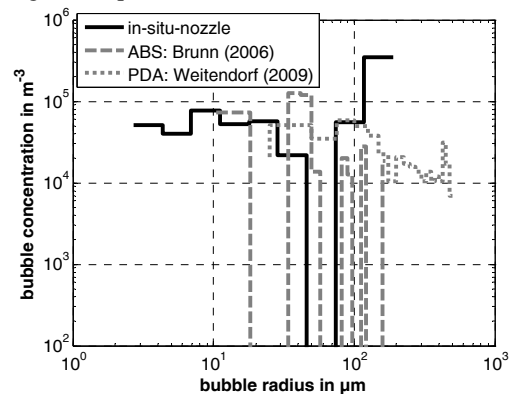


Figure 10: Bubble concentrations determined with the three different measuring principles in-situ-nozzle, Acoustic Bubble Spectrometer® (taken from [5]) and Phase Doppler Anemometry (taken from [13]) all conducted in degassed water. The in-situ-nozzle measurements were conducted on the suction side of the running test pump at 0.45 bar pump/nozzle inlet pressure, which corresponds to an operating point of the test pump free of cavitation. The resulting bubble radii are scaled with a static pressure of 1 bar.

Sensitivity of the measuring device

To further examine the capability of the measuring system of giving an approximation of the nuclei size distribution the pump inlet pressure/nozzle inlet pressure was reduced in order to change the nuclei size distribution. Figure 11 shows the accordant results for three different pressure values. Again the content of the dissolved air was at about 25 % saturation and a steady state was awaited before beginning with the respective series of measurement. It is seen that a reduction of the pressure at the mounting position and hence a stimulation of the growth of the nuclei does not lead to an increase in the detected radii or rather the calculated concentrations. This suggests the assumption that either the real nuclei size distribution was not varied as much as it was intended or that the in-situ-nozzle is not sensitive enough to detect a change in the nuclei size distribution. The latter one can be disproved by means of figure 12, which shows the nuclei concentrations on the pressure side of the test pump measured with the second in-situ-nozzle mounted in the pressure pipe. The two pressures indicated here

bear on the pump inlet pressure which in turn correspond to states free of cavitation and of about 20 % head drop ($p_1 = 0.15$ bar) respectively. In an operating point with a head drop of 20 % the blade channels are subject to large coherent vapour regions which according to experience should lead to firstly an increase of the concentration of the nuclei already present and secondly to a generation of new nuclei. Both effects can be seen in the graph. In order to also compare these results to those on the suction side of the pump the bubble radius is scaled to atmospheric pressure. By doing so it is found that the largest nuclei on the pressure side are not less than two orders of magnitude smaller than the ones on the suction side. Note that this is also the reason for choosing a linear scale of the abscissa in figure 12. Since both in-situ-nozzles are identical in construction and the measurements were conducted in exactly the same way, the nuclei must be subject to a significant shrinking due to diffusion of air from the nuclei into the surrounding liquid. Given a residence time of approximately two seconds between the pump inlet and the mounting position of the in-situ-nozzle in the pressure pipe, mass diffusion cannot be neglected for a bubble of a typical size of $10 \mu\text{m}$ according to the estimation of equation (11).

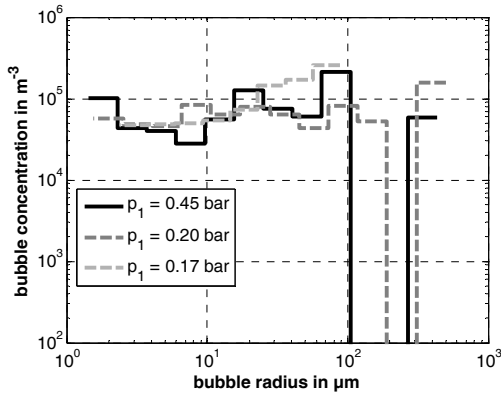


Figure 11: Bubble concentrations on the suction side of the running test pump at 0.45 bar, 0.20 bar and 0.17 bar pump inlet pressure. These correspond to operating points of the test pump firstly free of cavitation, secondly at cavitation inception and thirdly at about 3 % head drop. The bubble radii are scaled with a static pressure of 1 bar.

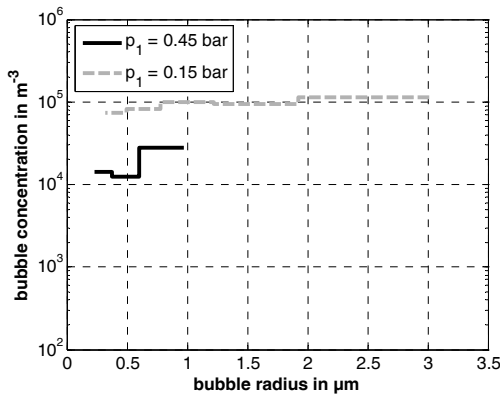


Figure 12: Bubble concentrations on the pressure side of the running test pump at 0.45 bar and 0.15 bar pump inlet pressure.

These correspond to operating points of the test pump firstly free of cavitation and secondly at about 20 % head drop. The bubble radii are scaled with a static pressure of 1 bar.

DISCUSSION

In this work a new device for the quantification of the water quality in hydraulic test installations is presented. The developed method is based on the measuring of the tensile strength directly within an operating hydraulic circuit by means of the in-situ-nozzle. In the subsequent evaluation process the ascertained values of the tensile strength are associated with the radii of the underlying spherical cavitation bubbles and hence an approximation of the current bubble size distribution is derived. This evaluation procedure is based on the overall assumption that the true bubble size distribution is homogeneous and remains in a steady state. With the additional assumption that the bubbles are not influenced by mass diffusion during their travel through the in-situ-nozzle the bubble size distributions in different pressure regions within the circuit can be compared to each other. This assumption has been proved to be justified for pure molecular diffusion. Apart from that the relevance of turbulent diffusion should be investigated in the future as well.

The results of the first experiments that were conducted to verify the functional capability of the measuring system first of all show a good agreement in the size range of the nuclei detected with other measuring systems. However, from this comparison it has been seen that both the qualitative trend of the bubble concentration and its order of magnitude appear to be strongly depended on the water conditions, i.e. the content of the dissolved air and/or the possible existence of a cavitation region. To get a better understanding of the fundamental interactions further experiments should be conducted in which the bubble size distribution at the mounting position of the in-situ-nozzle is varied explicitly.

In this context the subsequent measurements with both in-situ-nozzles have clearly shown two effects about the nuclei size distributions observed upstream and downstream of the test pump. Firstly the maximum size of the bubbles detected on the pressure side is about two orders of magnitude smaller than on the suction side, which is explainable only with the occurrence of diffusion of air from the bubbles into the liquid. Secondly it has been found that both the size range and the concentration of the bubbles downstream of the pump increase when the pump is subjected to a state of advanced cavitation.

The analysis of the first results presented here has demonstrated that the developed measuring method can be used to experimentally investigate the influence of different operating points of a hydraulic test installation on the corresponding nuclei content. Nevertheless further basic experiments should be conducted to get a deeper understanding of the measuring system in terms of the accessible sensitivity to a slight change in the boundary conditions.

CONCLUSION

With the overall objective of making more accurate predictions on the performance of centrifugal pumps with respect to different levels of cavitation reliable methods for the determination of the water quality in hydraulic installations

need to be developed. In combination with measurements of the content of dissolved air the in-situ-nozzle serves as a new device for quantifying the water quality in terms of the tensile strength and/or the concentration of cavitation nuclei. One of the advantages of the in-situ-nozzle by comparison to other measuring techniques is its simple way of integration into an either transparent or opaque hydraulic line of variable cross-section. This makes the in-situ-nozzle to be a convenient measuring device that can be easily mounted in various hydraulic installations.

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NOMENCLATURE

c_i	concentration of a single nucleus
D	diffusion coefficient
g	constant of gravity
H_{opt}	optimum hydraulic head
m_g	gas mass in the bubble
n	polytropic exponent
n_s	specific speed
N	total number of single events
$NPSHA$	available net positive suction head
$\Delta p_{crit.}$	tensile strength
p	static pressure
p_1	pump inlet pressure
p_2	pump outlet pressure
p_∞	pressure in the minimal cross-section
$p_{crit. \infty}$	critical pressure
p_g	partial pressure of the gas (air)
$p_{meas.}$	measured static pressure
$p_{tot. l.}$	total pressure at the pump inlet
$p_v(T_\infty)$	saturated vapour pressure
Q	flow rate
Q_i	flow rate required for cavitation inception
Q_{opt}	optimum flow rate
R	bubble radius
$R_{crit.}$	critical bubble radius
R_E	equilibrium bubble radius
R_g	specific gas constant of air
S	constant of capillarity
t_i	time of cavitation inception
t_D	diffusion time
Δt_k	time since previous event
T_∞	temperature
ΔV_k	volume associated with a single event
ρ	density

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