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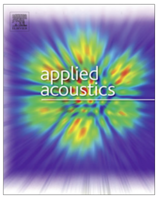

Cavitation dose in an ultrasonic cleaner and its dependence on experimental parameters

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A B S T R A C T

The aluminum foil erosion method is widely used in cavitation activity studies of ultrasonic cleaners. However, owing to its limited sensitivity, it is difficult to observe the effects of various experimental parameters on the cavitation activity using this method. In the present work, a higher-sensitivity method for quantifying cavitation activity as a cavitation dose based on passive cavitation detection was presented. The influences of various factors (e.g., insonation duration, driving power, gas content, temperature and cleaning agents) were studied for this system. The results showed that the cavitation dose became unstable over long insonation times, and that the instability was more significant at high power. Generally, the cavitation activity could be enhanced by increasing the power, gas content, and the concentration of a cleaning agent. However, due to the exhaustion of the cavitation gas nuclei, the cavitation activity might tune to saturate of even decrease slightly when some impact parameters (e.g., acoustic driving power, gas content and the concentration of the cleaning agent) are above a certain level of each of these parameters.

1. Introduction

When the intensity of ultrasound wave transmitting through a liquid is high enough, micron-sized gas bubbles can be excited to oscillate, expand, and implode violently. This phenomenon is called as "acoustic cavitation", which can induce localized, but extremely high temperatures and pressures in the collapsed cavities [1–4]. Acoustic cavitation is highly dependent on the acoustic parameters, such as the driving pressure and frequency, temperature, gas content, and the liquid properties. Many studies [5–9] have focused on the dependence of the cavitation intensity on these parameters for single bubbles. Putterman and co-workers [5,6] investigated the influence of driving pressure and temperature. Holzfuss et al. [7] found that using dual-frequency excitation could increase the cavitation intensity. Moreover, Chen et al. [8] investigated three kinds of sound waves: sinusoidal, rectangular, and triangular. They found that, for a fixed sound pressure amplitude, the intensity of cavitation activity reached the highest level when the single bubble was driven by a rectangular wave. Surface-active substances were also reported to be able to affect cavitation activities [9]. In recent years, high-intensity focused ultrasound (HIFU)-induced cavitation activities have been widely studied [10–14] both theoretically and experimentally for medical applications. The cavitation threshold (the minimum acoustic pressure for inducing cavitation) and cavitation dose (quantified cavitation activity) are important in diagnostic and therapeutic ultrasound applications. Therefore, it is necessary to investigate and optimize the factors that influence these properties. It has been shown both theoretically and experimentally that high viscosity of the liquid increases the cavitation threshold [10]. Roy et al. [11] pointed out that the cavitation threshold decreases at high suspended particle concentration and/or dissolved gas content. Tu et al. [13] studied the inertial cavitation (IC) dose produced with an ultrasound contrast agent (Optison®) using pulsed ultrasound. Their results showed that the pressure threshold of inertial cavitation decreases with the increasing Optison® concentration, and the IC dose (ICD) is raised sharply with the increases in the acoustic pulse length, driving pressure, the concentration of Optison® bubbles, or with the decrease in the acoustic pulse-repetition frequency. Wan et al. [14] also found that the cavitation dose increased with the decrease in the driving frequency and transmit aperture, or with the increase in the acoustic pulse length.

Ultrasonic cleaners are used in a wide range of industrial applications. The mechanism of action of the ultrasonic cleaner lies in

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the cavitation produced by the ultrasound field and microjets of fluid generated upon bubble collapse impacting the surface of the object being cleaned. The cavitation activity and distribution are important factors that determine the cleaning efficiency. Many studies have employed the aluminum foil erosion method to evaluate the cavitation activity [15–18]. Krefting et al. [15] found that erosion was weak at standing-wave nodes and that the bubble distribution was important for the formation of bubble structures. Wu et al. [16] also revealed that erosion mainly occurred near pressure antinodes. Jüschke and Koch [17] performed aluminum foil erosion tests in the temperature range from 10 to 45 °C and at different oxygen concentrations. They observed maximum erosion at 15 °C, and at a constant temperature of 20 °C, there was no correlation found between the extent of erosion and the oxygen concentration. Thus, it is hard to determine the impact of experimental parameters on the cavitation activity using the aluminum foil erosion method. The cavitation activity can also be detected by measuring the broadband acoustic emission spectrum [18]. The passive cavitation detection (PCD) method based on the measurement of the broadband acoustic emission spectrum is considerably more sensitive and quantitative than the aluminum foil erosion method. Thus, this is the preferred method for studying the effects of the acoustic parameters in medical studies [13,14,19].

In the present work, the cavitation activity of an ultrasonic cleaner was quantified as a cavitation dose based on the PCD method, and studied the influence of several parameters (insonation duration, driving power, gas content, temperature, and the presence and concentration of a cleaning agent) on the cavitation activity.

2. Measurement principles

During cavitation, there is very efficient and highly nonlinear conversion of acoustic energy to mechanical motion. The frequency spectrum produced by the oscillating cavitation bubble includes a fundamental frequency, harmonic, and sub-harmonic frequencies. When the cavitation bubble collapses, a broadband spectrum is produced. Therefore, the sound field can be deconstructed as shown in Fig. 1.

Both the incident sound source and cavitation produce acoustic waves at the fundamental and harmonic frequencies. Therefore, the continuous spectrum or sub-harmonic spectrum is preferred to quantify the cavitation intensity. The broad-band noise signals scattered from cavitation bubbles [11] can be detected by the PCD or active cavitation detection (ACD) systems. Some methods have been applied to quantitatively evaluate cavitation based on the acoustic emission spectrum [13,20,21]. Cavitation activity can be quantified as a relative measure (i.e. a “dose”), which is specific to the system and the experimental conditions. Using an ACD system combined with imaging equipment, cavitation can be directly observed. Compared with the ACD system, the PCD system has the advantage of a high signal-to-noise ratio and high sensitivity. Because of the high randomness of cavitation and its strong dependence on the experimental parameters, the cavitation activity should be estimated in terms of the amplitude or power over a certain period of time rather than at a particular moment.

3. Material and methods

The experimental system is schematically shown in Fig. 2. The experiments were carried out in a 505-mm × 300-mm × 200-mm ultrasonic cleaner (Elmasonic P300H, Elma-Hans Schmidbauer GmbH & Co. KG, Germany) with a 37-kHz working frequency. Deionized water (either partially degassed or air-saturated) was filled into a tank with a height of 120 mm. For the PCD measurements, a calibrated, 3–100-kHz, 10-mm-diameter, wide-band transducer (DBS-10, Hangzhou Ruili Technology CO., Ltd., China) was fixed 20 mm below the water surface to lower its influence on the sound field. A PCD “listening” transducer was used to detect the bubble scattering and emission signals, which were then digitized and stored by using an NI PXI System (NI PXI-1036, National Instruments Corp., United States). The stored waveforms were processed by a computer using a MATLAB program. Degassing was accomplished using a degasser (ERC-301, ERC INC., Japan) to control the air pressure in the reservoir while simultaneously recirculating the deionized water.

The signal processing method is shown in Fig. 3. The recorded waveforms were sampled at a frequency of 500 kHz (5 times higher than the maximum frequency of the transducer). The

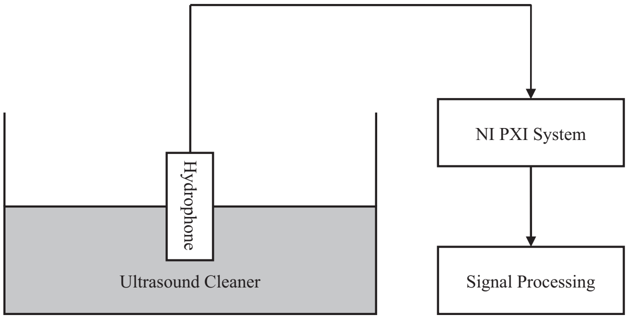

Fig. 2. The schematic diagram of the experimental setup.

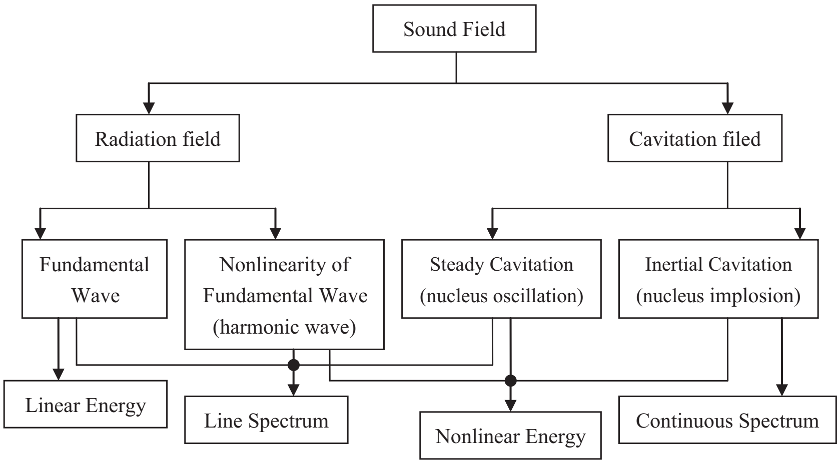

Fig. 1. Illustrative deconstruction of the sound field.

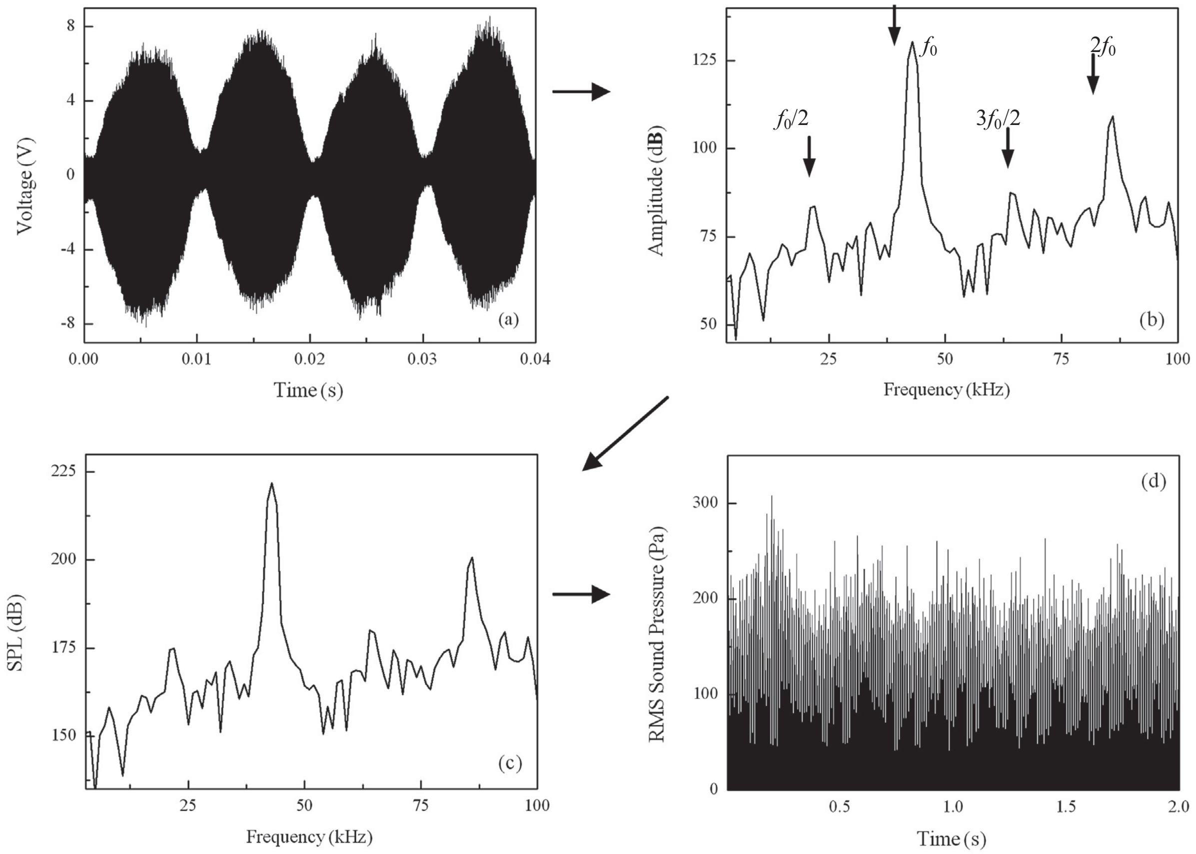

Fig. 3. Signal processing method for the quantification of cavitation dose. The collected cavitation signal from each segment (a) is windowed and converted into the frequency spectrum domain (b). The FFT amplitude is corrected for the sensitivity of the PCD transducer (c). The RMS pressure amplitude of the continuous and sub-harmonic components is evaluated and illustrated (d). The cavitation dose is calculated according to the integrated area in (d) (cumulative RMS FFT pressure amplitudes).

signals were then filtered by a seven-order Butterworth high-pass filter at a 200-Hz cut-off frequency to minimize disturbance at low frequency (e.g. from fluctuating water) (Fig. 3a). The whole sampling period for each measurement was 2 s. Every time series waveform of sampled signals was divided into 2000 equal segments. Each segment was first weighted with a Hanning window and then transformed to its frequency spectrum (Fig. 3b) by fast Fourier transform (FFT). Because the frequency response of the PCD transducer is not constant, the spectrum was corrected after calibrating the PCD transducer sensitivity (Fig. 3c). The cavitation signals (the continuous and sub-harmonic components) were picked up from the spectrum. These root-mean-square (RMS) FFT pressure amplitudes were then plotted for all detected waveforms, converting the signal back into the time domain (Fig. 3d). The cumulative cavitation dose was quantified as the integrated area under the curve over the whole sampling duration.

4. Results

The influences of insonation duration, driving power, gas content, temperature, and the presence of cleaning agents on the cavitation dose were investigated in turn. All other measurement conditions were held almost constant while the parameter under investigation was varied.

4.1. The effect of insonation duration

The temporal evolution of cavitation dose is plotted in Fig. 4 with the same initial temperature and gas content at driving powers of 114 W and 228 W. The cavitation dose was relatively constant for 30 min at a power of 114 W. However, when the power was increased to 228 W, the cavitation dose became unstable after 15 min. Therefore, the subsequent experiments were performed within 10 min to ensure the system was relatively stable.

4.2. The effect of acoustic driving power

Cavitation doses were measured when the driving power increased from 114 W to 380 W, and the results are presented in Fig. 5. The cavitation dose increased with increasing driving power up to 304 W, beyond which point it was relatively constant. Moreover, the standard deviation in the measurements was large at high power, indicating that cavitation becomes unstable under these conditions.

4.3. The effect of temperature

Because the saturated gas concentration depends on the solution temperature, deionized water was partially degassed to keep the oxygen concentration at 3.8 ± 0.2 mg/L. As shown in Fig. 6, the cavitation dose increases with the increasing temperature. However, the trend was different at the two different acoustic power levels: the cavitation dose increased with the temperature at a lower power of 114 W; while it firstly enhanced to its peak value and then dropped when the acoustic power reached a relatively higher level (viz., 228 W).

4.4. The effect of gas content

To study the effect of gas content on the cavitation activity, the deionized water was degassed to different oxygen contents. The

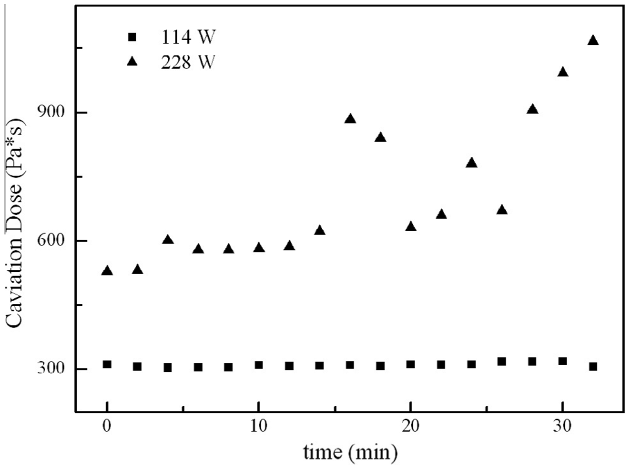

Fig. 4. Cavitation dose as a function of insonation time at driving powers of 114 W and 228 W; temperature: 27–30 °C, oxygen concentration: 7.0 ± 0.5 mg/L.

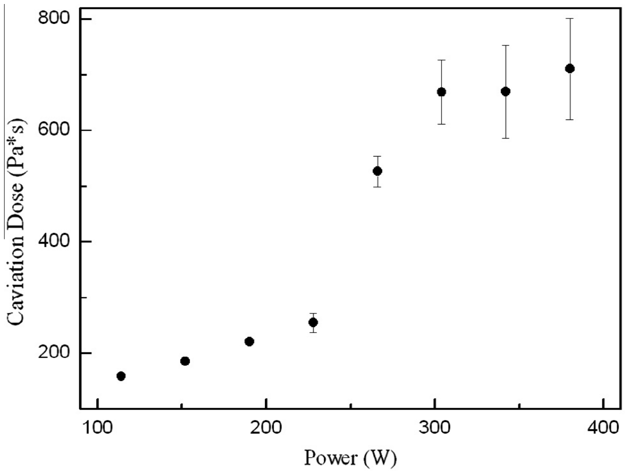

Fig. 5. Cavitation dose as a function of driving power; temperature: 22 ± 1 °C, oxygen concentration: 8.8 ± 0.4 mg/L.

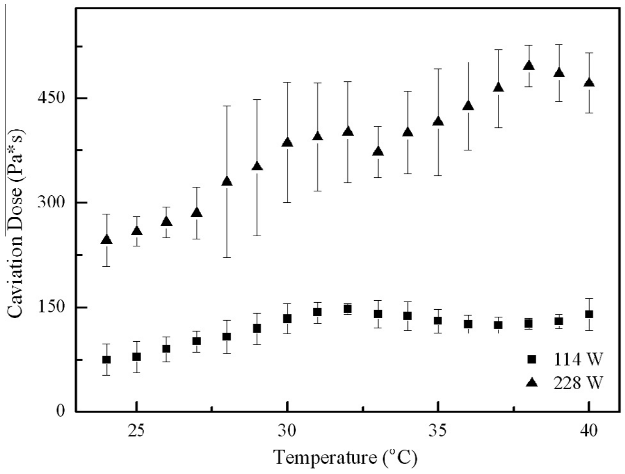

Fig. 6. Cavitation dose as a function of temperature at driving powers of 114 W and 228 W; oxygen concentration: 3.8 ± 0.2 mg/L.

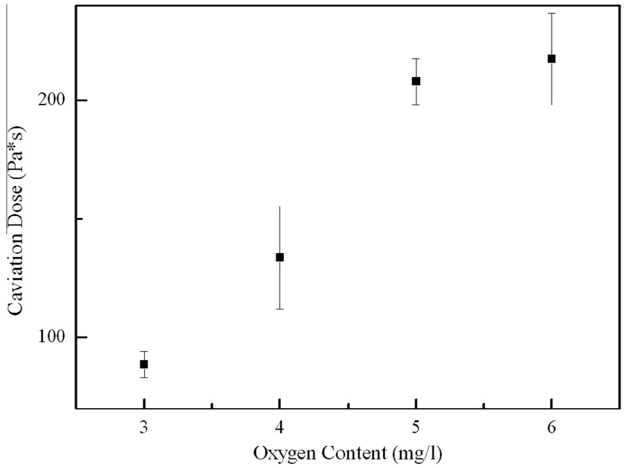

Fig. 7. Cavitation dose as a function of oxygen concentration; driving power: 114 W, temperature: 27 ± 1 °C.

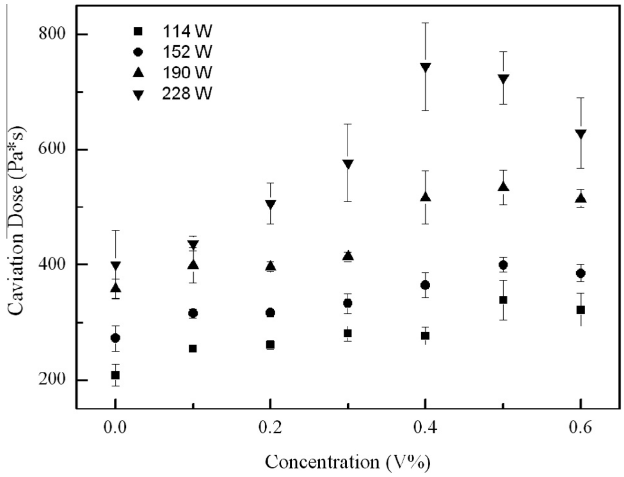

Fig. 8. Cavitation dose plotted as a function of the concentration of cleaning agent concentration under various driving powers; oxygen concentration: 5.7–5.8 mg/L, temperature: 34–35 °C.

cavitation dose increased with increasing oxygen content, while the rate of increase reduces at a high level of oxygen content (Fig. 7).

4.5. The effect of cleaning agent

Tap water, with or without chemical additives, is usually used as the liquid medium in ultrasonic cleaning baths. The influence of adding a cleaning agent was studied for a pH ~8.2 alkaline cleaning agent (Elma Lab Clean N10, Elma-Hans Schmidbauer GmbH & Co. KG, Germany). As plotted in Fig. 8, the cavitation activity increases with the raised concentration of cleaning agent up to about 0.5 vol.%, beyond which it slightly decreased.

5. Discussions

The cavitation activity is affected by nucleation, temperature, acoustic pressure and frequency, insonation duration, liquid properties, and other parameters. To control cavitation, it is necessary to control these parameters. The cavitation activity was estimated by the cumulative cavitation dose during a period of 2 s to study the influence of these parameters as well as the presence of a cleaning agent. Cavitation became unstable at long insonation times (Fig. 4), mainly because the transducers of the ultrasonic cleaner became unstable when it was operated for extended periods. It is also possible that this behavior is caused by changes in the gas content and temperature with time. The cavitation activity was also highly unstable at higher driving powers because environmental parameters (such as the temperature and gas content) change more significantly at higher power.

Cavitation becomes more intense when driving at higher power (Fig. 5). The same trend in cavitation activity with driving power was shown by Tu et al. [13]. The number of cavitation bubbles increases with increasing acoustic power. Furthermore, is has been shown that the average bubble size could be enlarged as a function of acoustic intensity up to a certain value [22]. The number and mean size reflect the broadband noise emitted and scattered by the bubbles: a larger bubble size or a greater number of bubbles produces a stronger broadband signal. However, when the acoustic power is raised to a certain value, the bubbles oscillate, grow, and collapse quickly. The cumulative cavitation dose will not further increase, and may even decrease, if the acoustic power is further increased. Based on multi-bubble studies, it has been pointed out that the stronger nonlinear oscillations at greater acoustic pressure cause the decrease in the bubble radius [23]. Although high power leads to intense cavitation, the cavitation dose becomes unstable and reaches a limiting value, and may even decrease under certain conditions.

The influence of ambient temperature was studied under a typical working temperature range of 24–40 °C at two different power levels. The cavitation activity was found to increase with water temperature at a power of 114 W (Fig. 6). However, when driven by a higher power of 228 W, the cavitation dose increased to a maximum then decreased with the increasing temperature. The dependence on the ultrasound intensity was also observed in sonoluminescence studies [24].

The influence of gas content was studied by measuring the cavitation dose at different oxygen concentrations (Fig. 7). A high gas content offers more available gas nuclei, increasing the likelihood that sufficient nuclei will be activated to establish a pattern of constant inertial cavitation. Therefore, a higher gas concentration results in a higher cavitation dose. This phenomenon is also supported by cavitation threshold studies [10,25]. In the present study, at a power of 114 W, the cavitation dose increased up to a concentration of 5 mg/L, beyond which it appeared to be relatively constant (Fig. 7). When the gas content increases, the cavitation activity affected by two competing factors that are associated with the increasing amount and volume density of the cavitation bubbles. One hand, they can cause nonlinear enhancement; on the other hand, they can also generate acoustic attenuation [26]. Moreover, the number of nucleation events is limited at a certain power, and at high gas concentrations becomes the limiting factor determining the cavitation dose.

There is a strong interdependence of the various parameters studied. The temperature increases with insonation time, particularly at high power, and long insonation times and high power cause the cavitation to become unstable. Additionally, the gas content decreases as an inverse function of temperature if the concentration is sufficiently high. Moreover, a relatively high temperature and high gas content can lead to intense cavitation; however, if the temperature is too high, the cavitation intensity decreases.

Tap water, with or without chemical additives, is usually used as the liquid medium in ultrasonic cleaning baths. Alkaline cleaning agents, which mainly contain surface-active solutes and alkaline chemicals, are commonly used to clean metal materials. In the present study, the presence of an alkaline cleaning agent increased the cavitation dose, which initially increased as a function of concentration (Fig. 8). However, the cavitation dose decreased at high cleaning agent concentrations. The effect of surface-active substances was discussed by Blatteau et al. [27]. They pointed out that the presence of surface-active substances improves the stabilization of gas nuclei. This means that surface-active substances increase cavitation nucleation and weaken bubble motion [28]. However, viscous adhesion attenuates the sound wave. When the concentration of the alkaline cleaning agent exceeds a certain value, the cavitation does is weakened. Therefore, care should be taken to add an appropriate amount of cleaning agent.

6. Conclusion

In this study, the cavitation activity in an ultrasonic cleaner was detected and quantified as a cumulative cavitation dose according to experimental measurements using PCD system. Highly reproducible results were obtained based on cavitation dose quantification, which was calculated from the cumulative broad-band acoustic noise signals resulting from cavitation activity. The effects of insonation duration, driving power, gas content, temperature and a cleaning agent were studied for this system. The results showed that cavitation becomes unstable at long insonation times, and that this instability is more pronounced at high power. Increasing the power, gas content, and adding a cleaning agent initially enhance cavitation. However, at sufficiently high values of these parameters and at high cleaning agent concentrations, the cavitation activity reduces. The influence of temperature depends on the ultrasound intensity. At a low power the cavitation activity increases with the temperature. At a relative high power, it initially increases with the increasing temperature, reaches a peak and then drops. Moreover, these parameters are strongly interdependent. Long insonation times and high power increase the temperature and lower the gas content. The gas content decreases when the temperature increases when the gas content in liquid is high enough. Therefore, cavitation in ultrasonic cleaners can be optimized by considering the effects and interactions of these factors.

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