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Time difference based measurement of ultrasonic cavitations in wastewater treatment①

Zhu Changping(朱昌平)②*, Wang Bin*, Liu Changwei*, Gong Runhang*, Liu Jing*, Ren Qinggong**, Han Qingbang*, Huang Bo*, Shan Minglei*, Tang Yibin*, Ni Caihua***

(* Jiangsu Key Laboratory of Power Transmission and Distribution Equipment Technology, Changzhou Key Laboratory of Sensor Networks and Environmental Sensing, Hohai University, Changzhou 213022, P. R. China)
(** School of Petrochemical Engineering, Changzhou University, Changzhou 213164, P. R. China)
(*** School of Chemical and Material Engineering, Jiangnan University, Wuxi 214122, P. R. China)

Abstract

Intensity of cavitation is significant in ultrasonic wastewater treatment, but is complicated to measure. A time difference based method of ultrasonic cavitation measurement is proposed. The time differences at different powers of 495kHz ultrasonic are measured in experiment in comparison with conductimetric method. Simulation results show that time difference and electrical conductivity are both approximately positive proportional to the ultrasonic power. The degradation of PNP solution verifies the availability in wastewater treatment by using ultrasonic.

Key words: cavitation intensity, sound velocity, time difference, wastewater treatment

0 Introduction

Ultrasonic is usually used in wastewater treatment and ultrasound cleaning[1]. During the process of ultrasonic, a lot of cavitation bubbles generate, grow, shrink and then collapse under a certain pressure, and this phenomenon is called cavitation[2]. Ultrasonic cavitation collects the energy of sound field and quickly releases the energy, which produces a hot spot with high temperature of 5000K and a high pressure up to thousands of atmospheric pressure during very short time (about several ns to μs). The intensity of cavitation is significant in ultrasonic process to control the sonochemistry production or ultrasonic cleaning efficiency. However, it is hard to measure the intensity of ultrasonic cavitation simply and directly as the complexity of the acoustic field distribution in an ultrasonic reactor.

The general methods of measuring ultrasonic cavitation are divided into physical and chemical methods such as the harmonic method[3], the electrical detecting method[4,5], sonoluminescence imaging method, and the iodine releasing method[6-9]. The cavitation nuclei in ultrasonic field can be observed directly with a high-speed photography and three-dimensional holographic technology nowadays[10], but is complicated and costly. In this work, a low-cost and easy-implement method is presented and is validate comparing with existing methods.

1 The principle of time difference method

There are many visible micro bubbles generated during the ultrasonic process because of the cavitation. The quantity of bubbles is increased as the intensity of cavitation is increased. Propagation velocities of sound waves are different in the liquid with different bubble quantities. Bubbles can be seen as obstacles when sound waves are propagating through them. The time difference method is a kind of macroscopic evaluation method which is suitable for real-time detection in the ultrasonic process experiment. The differences of sound transmission time (Δt) in water between with and without cavitation can be measured. And the intensity of ultrasonic cavitation can be described qualitatively.

The solution in ultrasonic process is suspending liquid. When there are some heterogenic things in the liquid, the velocity of sound travels in the solution can be expressed as follows[11]:

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② To whom correspondence should be addressed. E-mail: cpzhu5126081@163.com

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$$C = \frac{C_l}{\sqrt{(n_l + \frac{\rho_s}{\rho_l}n_s)(n_l + \frac{\beta_s}{\beta_l}n_s)}} \quad (1)$$

where C is the sound velocity in suspension, C_l is the sound velocity in pure fluid, n, ρ and β represent volume concentration, density and bulk compressibility respectively. The subscript s and l means suspended particles and pure fluid.

In order to union the experiment conditions, the concentration of liquid is expressed as x. So the expression of sound velocity is rewritten as

$$C = \frac{C_l}{\sqrt{(1 - x + \frac{\rho_s}{\rho_l}x)(1 - x + \frac{\beta_s}{\beta_l}x)}} \quad (2)$$

So the time difference of sound transmission is

$$\Delta t = \frac{L}{C_l}\left[\sqrt{1 + (\frac{\rho_s}{\rho_l} + \frac{\beta_s}{\beta_l} - 2)x + (\frac{\rho_s}{\rho_l} - 1)(\frac{\beta_s}{\beta_l} - 1)x^2} - 1\right] \quad (3)$$

For the small value of x, the square of x can be neglected:

$$\Delta t = \frac{L}{C_l}\left[\sqrt{1 + (\frac{\rho_s}{\rho_l} + \frac{\beta_s}{\beta_l} - 2)x} - 1\right] \quad (4)$$

The time difference can be expressed after Taylor expansions:

$$\Delta t = \frac{L}{2C_l}(\frac{\rho_s}{\rho_l} + \frac{\beta_s}{\beta_l} - 2)x \quad (5)$$

The sound velocity in fluid C_l is proportionate to the concentration of suspended particulates. In fact, for the small amount of suspended particulates, the solution shows liquid characteristics in view of the overall situation. So C_l can be got from the formula of sound velocity in fluid $C = \sqrt{K/\rho}$.

When concentration of liquid is x, the equivalent bulk modulus of suspension is $K = (1 - x/K_l + x/K_s)^{-1}$, and the equivalent density is $\rho = \rho_l(1 - x) + \rho_s x$. Then the time difference:

$$\Delta t = L\left\{\sqrt{(\frac{1-x}{K_l} + \frac{x}{K_s})[\rho_l(1-x) + \rho_s x]} - \sqrt{\frac{\rho_l}{K_l}}\right\} \quad (6)$$

Simplify and neglect the square of x to obtain the following:

$$\Delta t = L\sqrt{\frac{\rho_l}{K_l}}\left\{\sqrt{(\frac{1-x}{K_l} + \frac{x}{K_s})[\rho_l(1-x) + \rho_s x]} - 1\right\}$$
$$= L\sqrt{\frac{\rho_l}{K_l}}\left(\sqrt{1 + \frac{K_s\rho_s + K_l\rho_l - 2K_s\rho_l}{K_s\rho_l}x} - 1\right) \quad (7)$$

Using Taylor expansions:

$$\Delta t = L\sqrt{\frac{\rho_l}{K_l}}\frac{K_s\rho_s + K_l\rho_l - 2K_s\rho_l}{2K_s\rho_l}x \quad (8)$$

Eq. (8) shows that the time difference of sound is approximately proportional to the concentration of micro bubbles in solution. When the sound transmitting distance is fixed, the variation of time difference is characterized by the variation of sound velocity. The sound waves for measuring are quite easily interfered by the high power ultrasound in a reactor, so some measures are taken to minimise result errors. The sound frequency for measuring is 1 MHz to avoid most common frequency for ultrasonic treatment, and the directions of them are perpendicular to each other. All of the conditions in experiment are strictly controlled except for ultrasonic power.

2 Experiments

The experimental facility of time difference measurement is illustrated in Fig. 1. The sending and receiving transducer are embedded in a cylindrical reactor face to face with distance of 10cm. The sending transducer is driven by signal generator with a 1MHz sine wave, and the receiving transducer is connected with a 1MHz center frequency band - pass filter. The

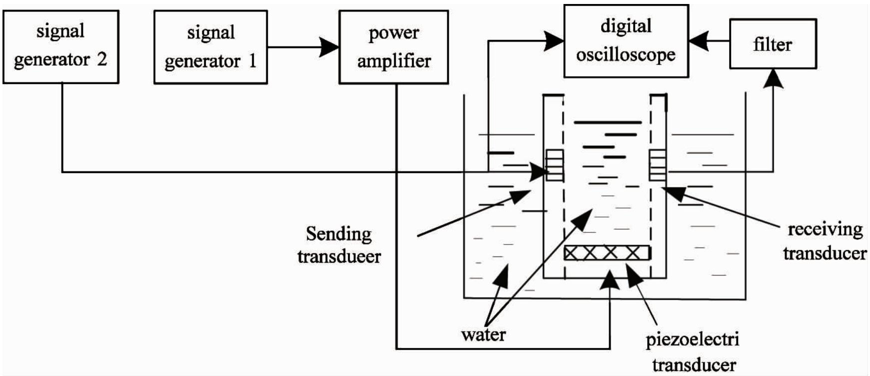

Fig. 1 Schematic diagram of time difference measurement

driving signal and receiving signal are monitored by a digital oscilloscope, which can calculate the phase offset of these two signals. A high power transducer with frequency of 495kHz is glued at the bottom of a reactor which is driven by a power amplifier connected with a signal generator. What's more, the lateral wall of vessel is filled with cooling water in order to keep the solution temperature at (25 ± 1) ℃.

The high power ultrasonic (495kHz) has impact on the measuring ultrasonic (1MHz). A band-pass filter is necessary to convert jitter receiving signal into stable signal. The receiving signals before and after filtering are shown in Fig. 2.

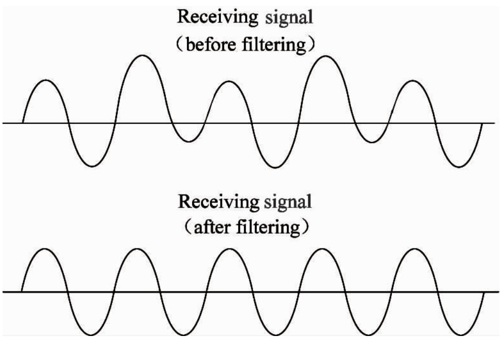

Fig. 2 The receiving signals before and after filtering

The signal received by the transducer is monitored on the digital oscilloscope after filtering out the noise. In Fig. 3, Δt_1 is sound propagation time with no cavitation, which is about 75μs. Δt_2 is the sound propagation time during cavitation. When the intensity of cavitation increases, Δt_2 will get longer.. The time difference $\Delta t = \Delta t_2 - \Delta t_1$ is the result, which represents the intensity of cavitation.

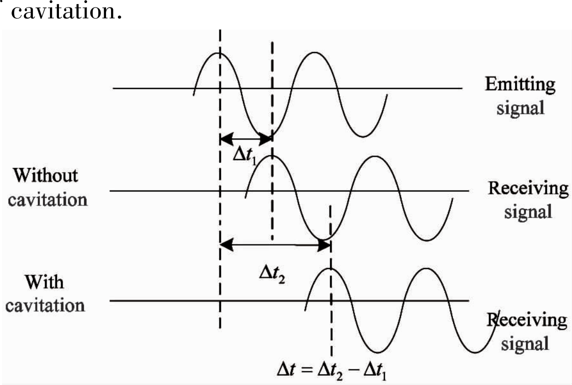

Fig. 3 The signal waves with cavitation and without cavitation

3 Results and discussion

3.1 Time difference at varies ultrasonic powers

The time difference is measured at different powers, which are ranged from 0 to 10W. The results are shown in Fig. 4. The electric power of transducer is approximately positive proportional to the acoustical power at a low range power of transducer[12]. The changing trend of Δt is similar to the changing trend of electrical power, which means Δt is proportional to the cavitation intensity. Meanwhile, when the ultrasonic power is strong enough, cavitation will be saturated that Δt will not increase any more.

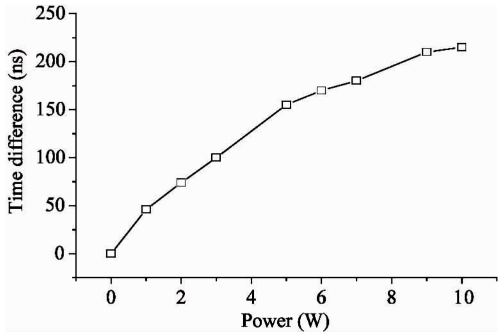

Fig. 4 The time difference at different powers

3.2 Comparison with conductimetric method

Conductimetric method is one of the traditional cavitation intensity measurements and is used to prove the correctness of time difference method in this paper. Usually N_2 and O_2 dissolved in water from air do not react with each other, but under the extreme condition caused by ultrasonic cavitation, they can react to form NO and NO_2, which will combine with water molecule to form HNO_3 and HNO_2, so that the electrical conductivity changed. The change of the conductivity can be measured by instrument and reflect the intensity of ultrasonic cavitation. The results of sound power, conductivity and time difference are shown in Fig. 5, which indicates that the change rule of time difference is similar to that of electrical conductivity. The method presented in this paper is as effective as the traditional methods.

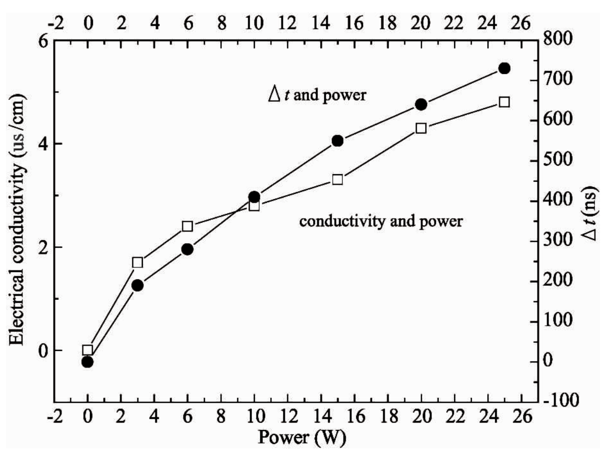

Fig. 5 The results of sound power, conductivity and time difference

3.3 Application in degradation of p-nitrophenol

Cavitation is the primary impetus in ultrasonic water treatment. The degradation of p-nitrophenol (PNP) was usually investigated in previous research. In this paper, the PNP water solution is used to be degraded by ultrasonic as an application of ultrasonic wastewater treatment. The concentration of PNP solution is 120mg/L, and 300mL of solution is added into the reactor. The temperature of solution is controlled at (25 ± 1)℃. Degradation rate of PNP is measured by a UV-VIS spectrophotometer. In order to observe the degradation of PNP solution, the same volume of deionized water is treated in the same condition and obtains spectrums as base lines in each experiments. The results of PNP degradation rate and its time difference are measured after 60 minutes 495 kHz ultrasonic treatment, and are shown in Fig. 6. It is obvious that the stronger intensity cavitation is, the higher degradation ratio of PNP will be. Usually, the concentration of solution makes susceptible to the time difference of sound propagation. But time difference could change if solvent of solution is organic such as benzene or carbon tetrachloride.

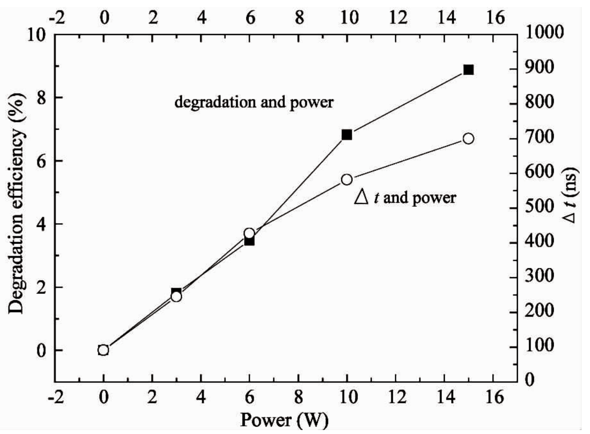

Fig. 6 The results of PNP degradation efficiency and time difference

4 Conclusions

In this paper, a new method of ultrasonic cavitation measurement is presented. The method applies the principles of sound velocity changing in cavitation solution. The time differences of sound at different powers of 495kHz ultrasonic are measured in experiment, and are compared with the electrical conductivity results at the same conditions. It is found that sound power is approximately positive proportional to the propagation time difference during the power range in experiment. This paper sets up an experiment for applying time difference method in degradation of PNP. The experimental results in this work are valuable reference for future research when the processing object is aqueous solution. Investigation of organic solution treatment using time difference method will be researched in the future. Time difference based measurement of ultrasonic cavitations is widely applicable to ultrasonic wastewater treatment.

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Zhu Changping, born in 1956. He is Ph. D and professor of Hohai University. He received his M. S degree from Huazhong University of Science & Technology in 2002 and Ph. D. in Communication and Information System from China University of Mining & Technology in 2010 respectively. His research interests include communication circuit and power ultrasonic technology.