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Experimental observation of the luminescence flash at the collapse phase of a bubble produced by pulsed discharge in water

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This letter presents an experimental observation of luminescence flash at the collapse phase of an oscillating bubble produced by a pulsed discharge in water. According to the high speed records, the flash lasts around tens of microseconds, which is much longer than the lifetime of laser and ultrasound induced luminescence flashes in nanoseconds and picoseconds, respectively. The pulse width of temperature waveform and minimum radius calculated at the collapse phase also show that the thermodynamic and dynamic signatures of the bubbles in this work are much larger than those of ultrasound and laser induced bubbles both in time and space scales. However, the peak temperature at the point of collapse is close to the results of ultrasound and laser induced bubbles. This result provides another possibility for accurate emission spectrum measurement other than amplification of the emitted light, such as increasing laser energy or sound energy or substituting water with sulphuric acid. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4935206]

The collapse of a cavitation bubble is the point of interest for many current researches because when a cavitation bubble collapses, a host of physical and chemical phenomena are observed. The temperature and pressure reach extremely high values. A flash of light, referred to as luminescence, is also radiated whether the cavitation bubble is generated by ultrasound,[1,2] laser,[3] or spark discharge.[4]

The luminescence effect produced by ultrasound has been studied over half a century. The sonoluminescence was first discovered in the 1930s,[5,6] though a definitive explanation of the phenomenon was not provided. In the 1950s, a cavitation on the face of a rod oscillating magnetrostrictively was studied to demonstrate that the emission of light did, in fact, occur at the point of collapse.[7] Meanwhile, the emitted light was also demonstrated as a result of the compression and adiabatic heating of the non-condensable gas within the bubble at the collapse time.[8] In the early 2000s, the experimental observations made by Taleyarkhan and his colleagues claimed evidence of nuclear fusion (termed bubble fusion) in cavitation bubble collapse.[9,10] However, the evidence of bubble fusion was questionable.[11] After that, Flannigan and Suslick made a milestone in the sonoluminescence study that confirmed plasma formation inside the cavitation bubble in sulphuric acid.[12]

Since the cavitation bubble produced by ultrasound is quite small and its energy is very low, it was difficult to analyze the emitted light quantitatively before photomultipliers became available.[13] During the 1970s, focused laser beam was applied to produce single cavitation bubble in a larger volume and with minimal disturbance of the surrounding medium.[14] Intensified CCD was also used to image the transient light emission process.[3] The plasma inside the bubble with a temperature around 6000 to 15 000 K was observed experimentally, and the results showed that it emitted significantly more photons than sonoluminescence.[15]

In contrast with the luminescence phenomena generated by ultrasound and laser, cavitation bubble and the accompanying luminescence caused by spark discharge has less literature available. Experiments by Vokurka and Plocek demonstrated similar thermal behavior in spark generated cavitation bubbles as the ultrasound and laser induced ones.[4] Generally, the spark discharge induced bubble is also highly localized and reproducible similar to the bubble induced by laser.[17] As shown in Fig. 1, in terms of maximum radius and oscillation time, the spark discharge generates bubbles with a maximum radius around one centimeter and an oscillation time about several milliseconds, which are almost two orders of magnitude higher than the bubbles generated by ultrasound and one order of

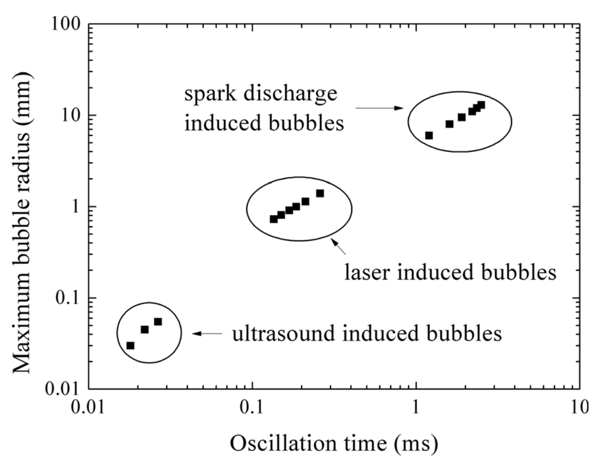

FIG. 1. Comparisons of maximum bubble radius and oscillation time among the bubbles produced by ultrasound,[1,2,16] laser,[3] and spark discharge.[17] These data are all based on ambient temperature and atmospheric pressure.

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magnitude higher than the bubbles generated by laser. Since ambient temperature and pressure have significant influence on the bubble dynamics,[18] all of these data are compared at atmospheric pressure and a similar ambient temperature. The results in Fig. 1 indicate that the spark discharge generated cavitation bubble can create a stronger luminescence effect, which can be attributed to the higher energy involved. In this letter, a high speed camera with normal CMOS sensor is used to record the luminescence flash at the collapse phase of an oscillating bubble produced by a pulsed discharge in water. The temperature inside the bubble is also calculated and compared with the results of ultrasound and laser induced bubbles. This work aims to provide an easy means to generate and observe an intensive luminescence effect caused by cavitation bubbles and to encourage continued efforts to its understanding and application.

The experimental setup is shown in Fig. 2. A homemade pulsed power source with output energy per pulse from 5 to 30 J is used to generate cavitation bubbles through pulsed discharge at the tip of a discharge electrode underwater. The discharge energy per pulse increases with a step of 5 J, which is varied by increasing the charging voltage of an energy storage capacitor with a capacitance of 2 μF. The discharge duration is around 60 μs, and the peak voltage varies from -2.0 to -3.9 kV. These electric parameters can be found in our previous work.[17,19] The tip radius of the discharge electrode is around 0.4 mm and is positioned at the center of a cylindrical reactor with four windows in two perpendicular directions. The diameter and volume of the reactor are 260 mm and 10 L, respectively, and the water conductivity and temperature inside are 53 mS/cm and 30 °C (298 K), respectively. At one side of the reactor, a beam of parallel light generated by a light emitting diode and a lens propagates through the bubble to make it visible to a high-speed camera with complementary metal-oxide-semiconductor (CMOS) sensor (NAC Merecam fx 6000) on the opposite side. The recording speed of the camera is 40 000 frames per second (fps), and the corresponding resolution is 512×60 pixel (bit density: 10). The exposure time for each frame is 1 μs, and the International Organization for Standardization (ISO) of the CMOS sensor is 1200. 12 dB gain and normal enhancement by the camera system are applied during the photo-taking process, and no digital intensification is applied in the data processing. The triggering of the pulsed power source and the high speed camera is synchronized by a homemade synchronizer with a time resolution less than 1 μs.

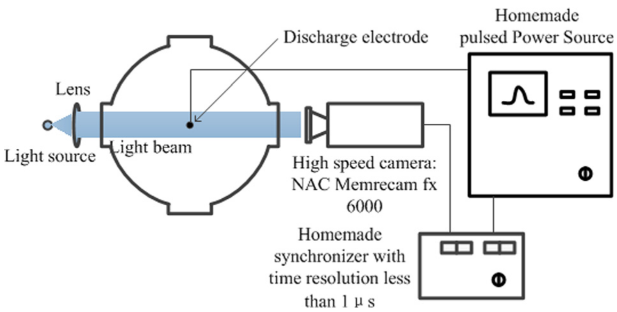

FIG. 2. Experimental setup.

As a cavitation bubble is formed during the dielectric breakdown in water induced by a focused laser beam,[3] an oscillating bubble can also be generated by the electric breakdown when a high voltage pulse is applied at an electrode tip underwater.[17] Taking the pulsed discharge and accompanying bubble oscillation with an energy of 30 J/pulse (actually, about 60% of the energy is delivered to the load since the circuit consumption, and 10% is consumed in the pre-discharge process, which means 15 J is available for the bubble oscillation; see Ref. 17) shown in Fig. 3, for example, the total number of frames for the first bubble oscillation process is 121, and the corresponding time is close to 3 ms. The oscillation process can be divided into expansion period and collapse period with a demarcation point when bubble radius reaches the maximum at the 51st frame. It indicates that the expansion speed is faster than the collapse speed, which is different from the ultrasound induced bubbles.[1,2,16] The light emission at the phase of electric pulsed discharge (when the discharge is initiated, the applied voltage is around -3.8 kV and the time is about 9 μs later than the beginning of the voltage application; see Ref. 17) is of higher intensity than the luminescence flash at the collapse phase (termed secondary discharge). Furthermore, three frames of the luminescence flash are recorded, and the emission intensity is obviously increased at the second frame. This means that the light is emitted not exactly at the time when bubble radius reaches its minimum and at least 25 μs before the end of collapse. So, the light emission has a duration in the order of microseconds, which is much longer than the laser induced luminescence flash in nanoseconds[16] and the ultrasound induced luminescence flash in picoseconds.[20] Fig. 4 gives the high speed records of luminescence flashes

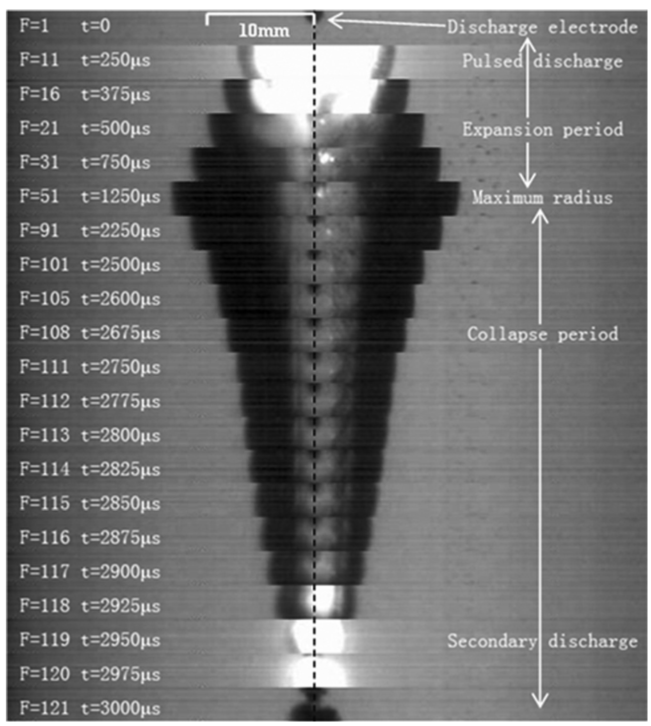

FIG. 3. Bubble oscillation produced by pulsed discharge with an energy per pulse of 30 J. The frame rate of high speed camera is 40 000 fps, the exposure time for each frame is 1 μs, and the ISO of the CMOS sensor is 1200. F: frame number and t: time.

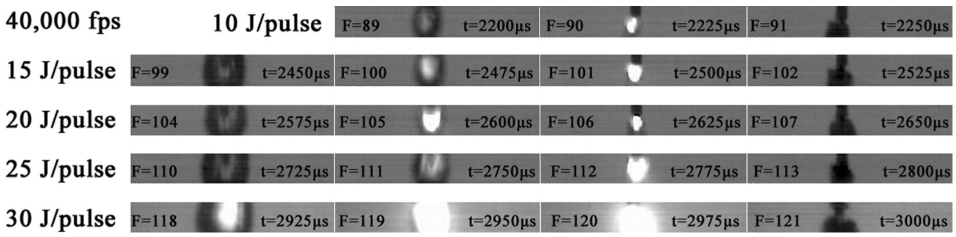

FIG. 4. High speed records of luminescence flashes in the collapse phase of cavitation bubbles produced by pulsed discharge with different discharge energies. F: frame number and t: time.

at the end of bubble collapse with the discharge energy from 10 to 30 J/pulse, while no flash can be observed for 5 J/pulse. For discharge energy of 10 J/pulse, only one frame of luminescence flash is recorded, and for other discharge energies, there are two or three frames of luminescence. Since the time interval between pulsed discharge and secondary discharge is around several milliseconds, close to the time of recombination in the secondary process of plasma,[21] the secondary discharge could be initiated by the residual charges inside the bubble when they get the energy from bubble compression.

For the study of luminescence flash at the collapse phase of a cavitation bubble, the most important topic is the temperature determination. Since the first observation of sonoluminescence, the measurement of temperature through emission spectrum fitting was first completed 70 years later. The difficulty of spectrum measurement is mainly due to the extremely short duration of luminescence flash. To make the temperature measurement more easy and accurate, the light emission must be intensified. Using concentrated aqueous H_2SO_4 solution is an effective way, with which collapsing bubbles released about 2700 times more light than the equivalent bubble in water.[12] However, the luminescence flash in this work, having a duration time around tens of microseconds, provides another possibility for accurate emission spectrum measurement.

Up till now, the temperature determination in most luminescence flash studies is completed using simulation methods. In our previous work, we also developed a model for the thermodynamic and dynamic of a cavitation bubble induced by pulsed discharge in water based on the ideal gas equation, Rayleigh's equation, and energy balance equation.[17] Taking the discharge energy of 30 J/pulse, for example, Fig. 5 gives the variations of bubble radius and inner temperature at the collapse phase. The pulse width (FWHM) of the temperature

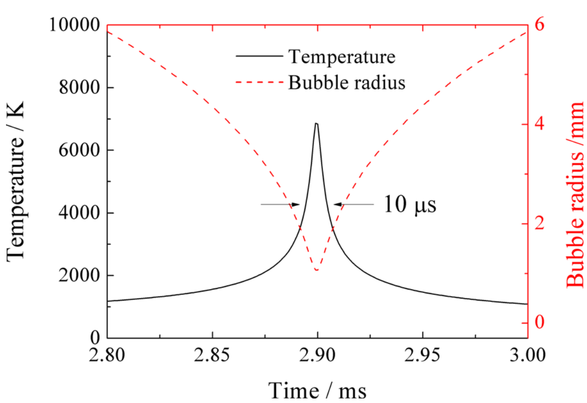

FIG. 5. Calculation results of the bubble radius and inner temperature during the collapse process of the bubble produced by pulsed discharge with energy of 30 J/pulse (around 15 J into the bubble oscillation).

waveform is around ten microseconds. Similar to the duration of luminescence flash, this result is also much larger than the pulse width of about 164 ps for the ultrasound generated bubbles[22] and the pulse width of about 20 ns of the laser induced bubbles.[15] According to these calculations, the minimum radius at the point of collapse is around 1.1 mm, which is comparable to the experimental result of 1.5 mm for a larger bubble produced by a spark discharge.[4] Unfortunately, this calculation result of minimum radius cannot be confirmed by the high speed records because the bubble is covered by the strong light emission at the end of collapse. The calculated collapse time is around 2.9 ms, as shown in Fig. 5, which is smaller than the measured one. This error could also be induced by the strong light emissions both at the beginning and the end of oscillation. The minimum radius in this work is much larger than the ones of the ultrasound and laser induced bubbles, which are several micrometers[16,23] and tens of micrometers,[15,24] respectively. So, all these results above indicate that the thermodynamic and dynamic signatures of bubbles generated by pulsed discharges in water are much larger than those of ultrasound and laser induced bubbles both in time and space scales.

In Fig. 5, the peak temperature at the point of collapse is about 7000 K, which is larger than the temperature at the surface of the bubble around 5900 K and smaller than the peak temperature of about 12 000 K calculated for larger spark discharge induced bubbles with maximum radii of 51 mm in Vokurka's work[4] and 42 mm in Lu's work,[25] respectively. For the ultrasound and laser induced bubbles, the peak temperature at the point of collapse ranges from about 7000 to 13 000 K.[15,21,26] The difference is not only determined by the bubble energy, but also induced by the assumptions of simulation models, especially the consideration of water vapor, mass transfer, and chemical reactions.[27] However, all these calculation results reasonably match the experimental results ranging from 8000 ± 1000 K to 15 200 ± 1900 K in Ref. 12.

In conclusion, this letter presents an experimental observation of luminescence flash at the collapse phase of an oscillating bubble produced by a pulsed discharge in water. According to the high speed records, the flash of light lasts for around tens of microseconds, which is much longer than the laser induced luminescence flash in nanoseconds and the ultrasound induced luminescence flash in picoseconds. The pulse width of temperature waveform and minimum radius calculated at the collapse phase also show that the thermodynamic and dynamic signatures of the bubbles in this work are much larger than those of the ultrasound and laser induced bubbles both in time and space scales. However, the peak temperature at the point of collapse is close to the results of the ultrasound and laser induced bubbles. This result provides another possibility for accurate emission spectrum measurement other than amplification of the emitted light, such as substituting water with sulphuric acid or increasing laser energy or sound energy.

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