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Explorations in Sonoluminescence

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Abstract

Single Bubble Sonoluminescence (SBSL) is the phenomena by which a bubble is levitated in a liquid medium and forced to oscillate using sound waves, which can make the bubble collapse violently enough to produce light. Various material parameters affect the light produced by these bubbles. This project provided an alternative methodology for the production of SBSL, as well as for data acquisition. Intensity measurements were obtained using a photomultiplier tube and spectral measurements were obtained using a fiber-optic spectrometer. The study focused on the effects of temperature and different liquid compositions on the intensity of the light produced by a SBSL bubble, as well as the spectrum produced by a sonoluminescing bubble. The results may contribute to a better understanding of the effects of material parameters on the light emission.

I. Introduction

In 1989 Filipe Gaitan, who was then a graduate student under the supervision of Dr. Lawrence Crum, discovered a method to trap a single sonoluminescent bubble in an acoustic standing wave. This was immediately titled Single Bubble Sonoluminescence (SBSL). When this phenomenon was discovered, it was evident that the intensity of the light produced by the bubble, the stability of the bubble, and the radius of the bubble were dependent upon parameters such as temperature and chemical composition. The study of these different material parameters has comprised a large portion of the research conducted in this field since its discovery. Advances over the years have made the reproduction of SBSL experiments much simpler and more effective. Although the process to produce SBSL has become well understood, the explanation as to why light is produced remains a point of contention. There is a wide range of theories including shock-waves, plasma, nuclear fusion, and the Casimir effect.

The research outlined in this manuscript had three primary foci. The first was to construct a cost effective alternative apparatus in which SBSL could be achieved. The second focus was on the study of the spectrum and intensity of the sonoluminescent bubble. These measurements not only provide us with information about the bubble itself, but also provide a control for subsequent experiments. The third focus was on the material parameters of the experiment, primarily temperature. Measurements were taken to refine previous results regarding the relationship between temperature and light intensity, and again, to provide a control for subsequent experiments.

II. Theory

To better understand the basic conditions for which sonoluminescence is attained, a discussion of fundamental acoustics is in order. Imagine an open pipe filled with water with pressure release surfaces at both ends. (Obviously this situation is physically unattainable because water would flow out of such a pipe, but it serves to illustrate the basic concepts involved.) When the pipe is brought to resonance, an acoustic standing wave is established within the pipe, creating both displacement and pressure waves within the pipe. Since the ends of the pipe are pressure release, the ends are the pressure nodes, or the points in which the pressure fluctuation is zero. Because the pressure fluctuations are zero, the motion of the water particles is maximized, thus corresponding to a displacement antinode. In the center of the pipe, the opposite situation is established: a pressure antinode and a displacement node. This means that at the center of the pipe the water molecules are not moving, but are also undergoing the largest pressure fluctuations. Sonoluminescence occurs when a bubble is positioned at the pressure (displacement) antinode (node). The bubble remains stationary but undergoes large pressure fluctuations, meaning that the bubble is expanding and compressing radially. With enough driving pressure the bubble oscillates rapidly and powerfully enough to implode upon itself, producing the star-like glow of sonoluminescence.

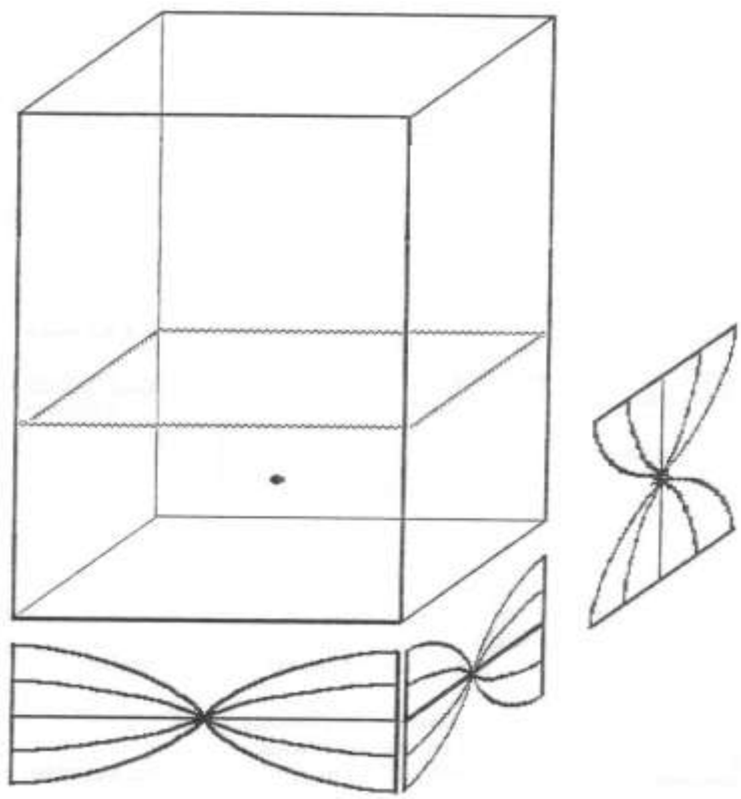

Figure 1: A visual representation of a levitating bubble at the displacement node.[1]

A container must be used in which resonance can easily be attained by producing an acoustic standing wave within it. Many SBSL experiments[5,6,7] use a glass spherical container for such a purpose. Such containers have proven successful, but also prove to be quite troublesome at times because some containers simply do not work due to impurities in the glass. Another option is the use of rectangular acrylic containers, which is a simple, effective and less expensive alternative. Advantages arise when one attempts to solve the wave equation in order to determine the resonant frequency of the container; the wave equation is

$$\frac{\partial^2\Psi}{\partial t^2} = c^2\nabla^2\Psi, \qquad \text{(Eqn. 1)}$$

where Ψ is the wave function, *t* is time and *c* is the speed of sound in the medium. The acoustic properties of glass make Eqn. 1 very complicated, and render the theoretical resonant frequency a rough approximation for the experimental resonant frequency. The acrylic cell has a distinct advantage because its acoustic properties are very similar to that of water. The system can then be assumed as homogenous as the walls of the cell are pressure release, meaning the acoustic pressure is zero. (The cell was placed upon a foam block to ensure that the bottom was also pressure release). The geometry of the cell, rectangular rather than spherical, makes the solution even easier because the separation of variables technique can then be used to yield:

$$f = \frac{c}{2}\sqrt{\frac{N_x^2}{L_x^2} + \frac{N_y^2}{L_y^2} + \frac{N_z^2}{L_z^2}}, \qquad \text{(Eqn.2)}$$

where *f* is the resonant frequency, N_x, N_y, N_z are the mode numbers and L_x, L_y, L_z are the dimensions of the cell.

In this project the acoustic standing wave is produced by an acoustic horn that is placed in the solution through an opening in the top of the acrylic cell. This requires resonance-matching between the horn and the acrylic cell; since the resonant frequency of the acoustic horn is known (26 kHz), Eqn. 2 is not used to find the resonant frequency of the cell, but rather to find the height of the water; L_z.

The experimental setup includes a drive circuit that provides the power to produce acoustic standing wave in the acrylic cell. The setup is rather straight- forward and can be seen in Fig. 2, but in order to achieve SBSL with this particular apparatus, the resonance in the electric circuit must match that of the acoustic horn and acrylic cell. To create electrical resonance in a circuit the inductive reactance and capacitive reactance must be equal (which can be observed when the voltage and current are in phase with one another). Since the acoustic horn in the simplest sense is a stack of capacitors, the circuit can be considered an LRC circuit. Resonance in an LRC circuit is given by:

$$\omega_d = 1/\sqrt{LC}, \qquad \text{(Eqn. 3)}$$

where ω_d is the driving frequency, L is inductance and C is capacitance. Using the resonant frequency (26 kHz) and the capacitance (12.0 nF) of the acoustic horn, the calculated required inductance in the circuit is 3.1 mH. Therefore, three 10.0 mH inductors were connected in parallel to make 3.33 mH and added to the circuit. This value proved to be sufficient in driving the circuit to resonance.

The stability and intensity of light produced by a sonoluminescing bubble is dependent upon the material properties of the solution in which the bubble is seeded, as well as the chemical composition of the bubble itself. In regard to the solution, it is well documented[2,3,4] that viscosity and vapor pressure play a large role in the shape stability of the bubble as well as the overall light intensity output of the bubble. An increase in viscosity reduces shape instabilities of the bubble, this increases the ambient radius of the bubble which improves the overall stability and allows it to be driven at higher pressures[2]. A decrease in vapor pressure reduces the amount of pressure within the bubble itself which in turn must be compensated by an increase in the driving pressure. If the bubble can remain stable while the driving pressure increases, the intensity of the light produced increases[2,4]. The easiest and most replicable method of changing these material properties is by changing the temperature of the solution. A decrease in temperature increases the viscosity and decreases the vapor pressure simultaneously, yielding a more stable and luminescent bubble. Both experimental and theoretical research has been done to confirm these claims[2,3,4]. The use of different solvents including glycerol and sulfuric acid has been known to increase the stability and intensity of SBSL by affecting the material parameters in a similar fashion[5,6,7].

III. Methods

A. Setup

The specific experimental setup was created primarily based upon its ability to be reproduced with a strict budget in mind. The SBSL-producing setup is adapted from previous work conducted by Aric Meyer at Grand Valley State University[1]; this project extended the previous work by adding equipment to measure the intensity and spectrum of the sonoluminescing bubble. Fig. 2 shows the complete experimental setup including the appropriate measurement systems.

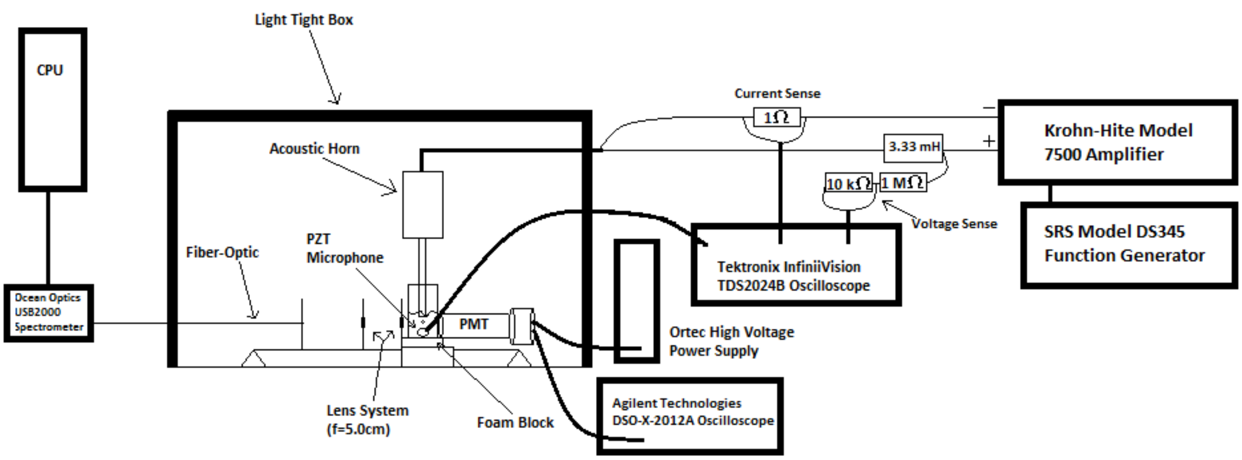

Figure 2: The experimental setup of the successful SBSL experiment.

The drive circuit was composed of a function generator (SRS Model DS345) that produced a sinusoidal electrical signal which was in turn connected to an audio amplifier (Krohn-Hite Model 7500) that increased the strength of the signal. This alternating voltage was connected to a system of inductors that tuned the electrical circuit to resonance. The resulting high amplitude signal drove an acoustic horn into resonance, and the horn was lowered approximately 1.0 mm into a solution contained within a rectangular acrylic cell (5.8 cm x 5.8 cm x 10.0 cm). The resonant frequency of the acrylic cell is dependent upon the amount of solution in the cell. A piezoelectric transducer (PZT) was epoxied to the acrylic cell and connected to an oscilloscope to act as a microphone in order to monitor the sound field in the cell. A Photomultiplier Tube (PMT) powered by a separate power supply (Ortic High Voltage Power Supply) was placed flush against the acrylic cell and connected to an oscilloscope to measure the intensity of the light produced by the bubble. On the opposite side of the acrylic cell a system of two lenses with focal lengths of 5.0 cm were used to focus light produced by the bubble onto a 1.0 mm diameter fiber-optic spectrometer (Ocean Optics USB2000). The spectral data was analyzed using the SpectraSuite software provided by Ocean Optics.

Stability and consistency of the system is very important, especially because of the sensitive nature of the measurement equipment. To ensure a controlled environment, a black wooden box (29 in. x 18 in. x 18 in.) was constructed to house the apparatus to eliminate ambient light. The front cover of the box was mounted using magnetic attachments and could be removed to gain access to the experiment.

In order to successfully focus the light from the bubble onto the spectrometer; the acrylic chamber, lens system, and fiber-optic cable needed to remain stationary for a long period of time. This was achieved using of an optical bench on which the lens system and fiber-optic were mounted using magnets. This allowed the lenses and fiber-optic to be moved for calibration purposes, but remain stable after calibration. The acrylic cell was not mounted, but was placed on a foam pad on top of a platform mounted to the optical bench, which was necessary because the acrylic cell would have to be removed periodically to change solutions. The platform was never moved, ensuring that the container would be placed in the same location for every experimental run.

B. Procedure

1. Producing SBSL

SBSL cannot be achieved without proper degassing of the solution in which the bubble will be levitating. Different solutions were attempted, but the only solution used in which measurements could be recorded was water. Purified, deionized water was poured into an Erlenmeyer flask and brought to a rapid boil. The water was boiled for fifteen minutes, then sealed and placed in a refrigerator to cool. After cooling, the water was poured into the acrylic chamber, the height of which was determined by the value of L_z in Eqn. 2. Since the acrylic cell and acoustic horn must be simultaneously in resonance in order for SBSL to be achieved, the function generator was set to the known resonant frequency of 26 kHz for the acoustic horn and varied by 10 Hz until the maximum signal was detected with the microphone. Once the resonant frequency was found, the driving signal was slowly increased while bubbles were seeded into the solution using a small hypodermic syringe. Stable SBSL could be consistently attained when the microphone read between 4.00 V and 8.00 V, dependent upon the degasification and temperature of the solution. As time went on, the degasification was compromised due to exposure to air. (However, the solution remained usable for upwards to an hour.) It was experimentally observed that as the temperature rose, the upper limit of the SBSL regime decreased and the stable SBSL regime shrank.

2. <u>Spectral and Intensity Measurements</u>

Obtaining spectral measurements was particularly difficult because of the careful alignment required between the bubble, the lenses, and the fiber-optic. The bubble, when stable and luminescing, is about the size of a pinhead; while the fiber-optic has only a 1.0 mm diameter opening in which the light can enter. Thus the use of two lenses (4.0 cm diameter) was necessary; one to gather light as a collimated beam and the other to focus that beam into a point on the fiber-optic. The lenses were mounted on the optical bench using magnets so they could be adjusted in four directions, but always remained in line with the bubble and the fiber-optic. The fiber-optic was placed in a white cardboard screen that was attached to the optical bench, (again with the use of magnets). If the light was not focused on the fiber-optic it could be seen on the white screen, and the lenses could be adjusted accordingly. When the light was properly focused on the fiber-optic, the box was sealed and the spectral measurement was taken using the *SpectraSuite* software.

Conversely, obtaining intensity measurements was a simple, straight forward process. The PMT was placed flush against the acrylic cell and was large enough (5.0 cm diameter) to span the majority of the container width. The PMT was powered by a high voltage power supply capable of reaching 3000 V, but successful intensity readings were found between 2000 V and 2500 V. With a stable sonoluminescing bubble in the chamber, the box was closed and the intensity measurements were recorded as a voltage peak on an oscilloscope.

III. <u>Results</u>

A. Spectral Measurements

Spectral measurements were taken in purified degassed water at temperatures ranging from 5℃ to 20℃. Each measurement was taken with a 40 second integration time with 5 scans to average, meaning that each measurement took 300 seconds total. The integration time and scans to average values were settled upon based on quality of results and the average lifespan of the sonoluminescing bubble. Due to the long time required to take each measurement, exact temperatures of the solution for each spectral measurement could not be recorded. This did not prove problematic, as all spectra recorded varied by only 10 nm in peak wavelength. Fig. 3 shows a successful spectral measurement conducted between the range of 5.0℃ and 19.0℃.

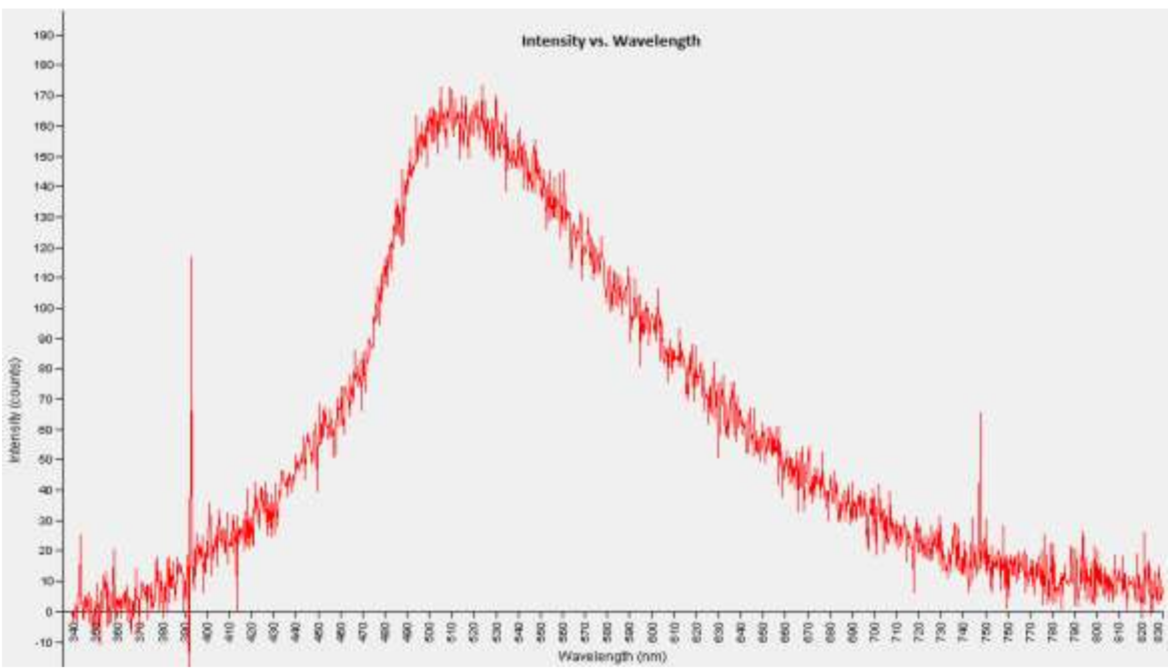

Figure 3: A successful SBSL spectra with a peak wavelength of 510 nm.

This spectral measurement shows a smooth curve over a range of 340 nm to 830 nm. This particular spectrum is typical of the spectral measurements taken in terms of shape, range of wavelength, and peak wavelength.

B. Temperature Dependence of Light Intensity

Measurements were taken from 5.0℃ to 19.0℃ using purified degassed water to experimentally confirm the dependence of temperature on the light intensity produced by a SBSL bubble. A total of 44 measurements were conducted using different water samples. Each sample was prepared using the same process, but there is no guarantee that the samples were uniformly degassed. Therefore, these measurements were not taken to determine exact intensities, but rather relative intensities due to the temperature of the water. Fig. 4(a) and (b) display the results and show conclusive evidence of an inverse relationship between temperature and light intensity.

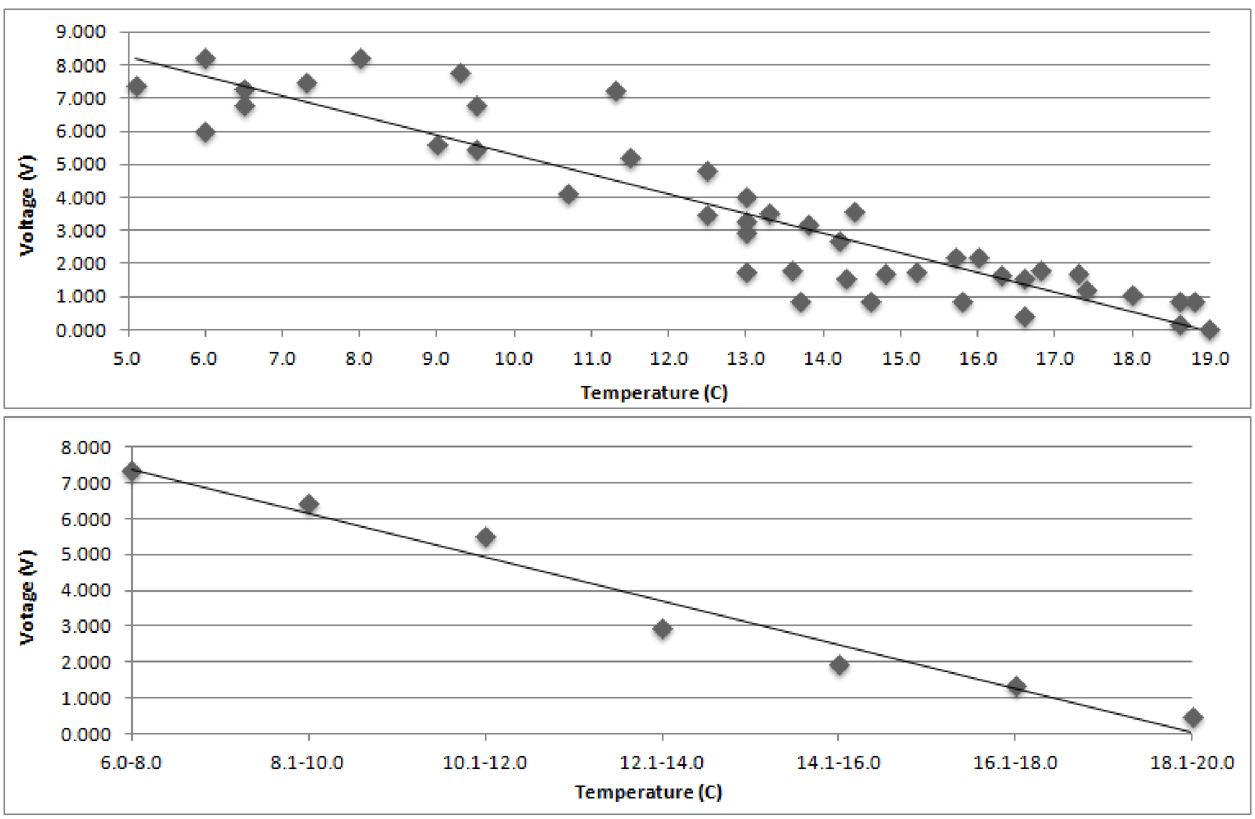

Figure 4: Intensity dependence on temperature. Fig. 4(a) (top) shows peak voltages of 44 experimental runs, whereas 4(b) (bottom) shows the same data sorted into 2˚C bins. Both figures show an inverse linear relationship between intensity and temperature, with R^2 values of 0.8403 and 0.9664, respectively.

C. Attempts Using a Glycerin/Water Solution

Many trials using a concentration of 10% glycerol in water were conducted with unsatisfactory results. Many problems arose in degassing the solution. Degassing techniques including boiling, sonification, vacuum pumping, and sparging (bubble doping) were used, but no significant data could be collected. It was found that SBSL was possible using these techniques, but stability was a constant issue. The bubble would 'dance' and 'jitter' about the displacement node, never fully coming to a stop and allowing a spectral measurement to be taken. On many occasions the bubble would seem to be in a cycle in which it would luminescence, increase in size and intensity until self-destruction, then re-seed itself and repeat the process. It is noteworthy to add that Multi-Bubble Sonoluminescence (MBSL) was achieved quite easily using a glycerin/water solution. By simply increasing the driving signal above the SBSL regime, MBSL was seen.

IV. Discussion

A. Spectral Measurements

Fig. 3 shows a spectral measurement that resembles a blackbody curve. Previous research [5,6,7,8] has suggested that SL bubbles are blackbodies, and our measurements support such an interpretation. If one considers a SBSL bubble to be a blackbody, the wavelength peak is of considerable interest, since it can be related to the temperature of the gas inside the bubble. More than ten spectral measurements were taken all of which have a peak wavelength between 500 nm and 515 nm. The particular spectrum in Fig. 3 has a peak wavelength of 510 nm. Wien's displacement law for an ideal blackbody relates the temperature T of the emitting body to the peak wavelength λ_{max} as follows:

$$\lambda_{max} T = b, \qquad \text{(Eqn.4)}$$

where *b* is Wien's displacement constant, equal to 2,897,768.5(51) nm·K. Eqn 4 estimates temperature of gas inside the bubble to be 5680 K, which is approximately the surface temperature of the sun. One other study[6] reported temperatures reaching 10,000 K in the center of the bubble. Our spectrum measurements are significant because the smoothness of our spectral curves compared to an earlier study[7] provides more definitive evidence for blackbody radiation.

B. Intensity Measurements

It is generally accepted that an inverse relationship between the solution temperature and the light intensity produced exists[2,3,4], but literature taking the contrary stance exists[9]. Conducting experiments to test this relationship served purposeful to not only affirm the inverse relationship, but also to serve as a control when subsequent research is conducted. Fig. 4 shows evidence that indeed an inverse relationship does exist. One will notice, however, that there are significantly more data points above 12.0℃. It was experimentally observed that although intensity did (on average) increase as the temperature decreased, the achievement of SBSL and the overall stability of the bubble increased within the temperature range of approximately 12.0℃ to 18.0℃. This is an interesting result, because previous studies[2,3,4] would predict that the stability of the bubble would also increase as the temperature decreases. The reason for this oddity remains unknown, but data below 12.0℃ were more difficult to attain. Nevertheless, our data provide sufficient evidence to support the inverse relationship between temperature and light intensity.

V. Conclusion and Future Work

A unique apparatus capable of acquiring simultaneous spectral and intensity measurements of a SBSL experiment was successfully constructed. A plethora of spectral measurements was acquired using a fiber-optic spectrometer, and the data provided firm support of blackbody radiation. Measurements taken with a PMT provided conclusive evidence of the inverse relationship between the temperature of the solution and the light intensity.

Research into SBSL at GVSU is still in progress. We plan to explore various substrates and additives; for example, the use of sulfuric acid has been suggested by Dr. Lawrence Crum[10] due to its ability to produce light intensities upwards of 10,000 times greater than those in water. (However we would need to change key aspects of the apparatus in order to safely contain sulfuric acid.)

IV. Acknowledgements

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