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Experimental Investigation of the Muzzle Blast for the Amphibious Rifles when Shooting Underwater

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ABSTRACT

Designed for amphibious combat forces, the amphibious rifle is a revolutionary new kind of weapon. This firearm's design and the determination of the effect of shooting on the shooter are both dependent on the development of the underwater muzzle blast. In this work, an experiment to evaluate the muzzle blast overpressure and gas bubble characteristics of an amphibious rifle when shooting underwater is performed in order to better understand the weapon's capabilities. This inquiry is focused on the 5.56 mm amphibious rifle with 5.56x45 mm underwater ammunition. The results of the experiments indicated that the Rayleigh-Plesset equation may be used to describe and predict the size of gas bubbles. The experimental data may be utilized to compute the law of change of overpressure based on the experimental results. Also, it is a very important base for studying, designing, making, and mastering weapon technology, which are all very important steps in the development of weapon technology.

Keywords: Amphibious rifle; Underwater shoot; Gas bubble; Overpressure; Muzzle blast

1. INTRODUCTION

The development of military equipment and weapons that are adaptable to a variety of terrain plays an important role in the conduct of military operations and helps to improve the combat effectiveness of the soldiers who use such tools. This is a very important component of the armed forces to have. To clarify, a weapon that has been built expressly for use in conditions that are submerged in water is referred to as an underwater firearm. They are a part of the military arsenals of a variety of countries across the world. Rather than conventional gunshots, underwater rifles and needle weapons frequently fire flechettes or spear-like bolts. One option is to run them on compressed gas[1] . Amphibious rifles are one of the newest forms of armament that may be employed to accomplish a variety of functions in warfare in the air and on the water. When a gun is fired into the air, the high-pressure, high-temperature propellant gas that comes out of the muzzle creates a complicated flow field called the muzzle flow field.

Because of the weapon's relevance and the requirement for special forces to make widespread use of it in battle, many scientists are especially interested in the development of such weapons. However, because of the significance of the material and the inherent sensitivity of the copyright issues, only a few in-depth studies have been conducted and made widely available. Several academics have presented their perspectives on this barrier,[2–5] using a variety of methodological approaches, and they can be discussed as follows. Hristov *et al*.[6] demonstrated how a Computational Fluid Dynamics (CFD) model was used to determine the muzzle blast overpressure and its physical manifestations, as well as to validate the model using key parameter measurements. Numerical simulations of the complicated gas-dynamic process of propellant gases expelled from the barrel after firing were conducted using unsteady Reynolds-averaged Navier-Stokes equations (URANS) and a matching turbulence model. Then, the research team of Hristov[7] discussed muzzle blast overpressure simulations and measurements, as well as its physical manifestations. The use of a silencer may have a significant effect on the strength of the overpressure. A silencer may be thought of as a combination of an acoustic transducer and a waveguide. Guo and colleagues[8] presented an interesting study. Due to the muzzle blast flow field, high-pressure waves across the gun barrel are crucial. Meanwhile, the gun's impulsive loudness does harm to people and the environment. As a result, in the typical turbulence model and axial symmetry N-S equations, reducing muzzle blast overpressure during the blast flow has gained popularity. The muzzle brake is meant to reduce noise. Using a muzzle brake reduces overpressure by around 74% compared to using an anti-aircraft gun without one. Kurbatskii and coworkers[9] presented the accurate and efficient numerical prediction of stationary and moving shock waves that may be accomplished using (CFD) and the use of solution-based mesh adaption (refinement and coarsening).

Until now, it has been very difficult to anticipate moving shock waves of varying intensities inside the same fluid effectively in a computer domain. The suggested numerical technique is based on a shock-detecting methodology that employs the normal to a shock's Mach number as a shock-identification parameter to monitor both stationary and moving shock waves of varying intensities. Cler., *et al*.[10] used precise

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near-field wave propagation modeling to calculate the blast wave overpressure of high-caliber muzzle brakes.

However, the muzzle blast phenomenon of underwater shots and air shots differ due to the density difference between water and air. If we want to better comprehend underwater shooting, we cannot simply apply the concept of a shot in the air to a shot underwater. The underwater explosive gas bubble phenomenon has piqued the interest of many researchers[11-16]. Several approaches for computing free-field blast characteristics in underwater explosions, such as pressure and impulse, were described by Kowsarinia, *et al.*[11] These techniques will be compared to experimental results of underwater detonation with a Hexogen explosive charge, which will be conducted by the author. Liu and his team[12] analysed numerically the whole process of shock wave creation and propagation, as well as the bubble formation and impulse of an underwater explosion, using the flow-out boundary and variable step-size multi-material Euler method. The calculated findings illustrate the energy output characteristics of an underwater explosion induced by a TNT charge, establishing a critical scientific foundation for charge formulation and enhancement of destructive effects on the underwater target. Huang and colleagues[13] performed a numerical simulation of underwater explosions using the ANSYS-AUTODYN explicit program for nonlinear dynamics, which was provided by ANSYS Century Dynamics, Inc. (Canonsburg, PA, USA).

Tuan and colleagues[17] utilised the Cosserat model to describe non-stationary processes in composite constructions. Unsteady axisymmetric kinematic perturbations propagating across space from an isotropic pseudo-elastic Cosserat medium are examined. The medium's motion is described by three equations, with the origin at the cavity's center and nonzero displacement vector and rotation field potential components. Holt and Lee Culver[14] employed three methods to invert observations and estimate the bubble population, each of which he developed himself. It has been decided to utilize the bubble population estimates to construct a model for the bubble population that would follow from an undersea explosion. Singh[15] investigated the propagation and attenuation of spherical shock waves using Whitham's approach and the Energy Hypothesis method. Deshpande *et al.*[16] made an underwater shock simulator to load materials with stress and test structures in the lab while they are underwater.

It is evident that only a small amount of research has been conducted on this issue for the underwater shot. As a result, this work first conducts an experimental analysis of the muzzle blast for amphibious rifles while firing underwater, and then compares the experimental results to those produced by the analytical solution based on the Rayleigh-Plesset Eqn.[18-21]. The results of this study will have a big impact on how amphibious assault rifles are made, designed, and developed in the future.

The remainder of this paper is organized as follows. In Section 2, the theoretical foundations are briefly presented. Experiments, findings, and comments are all detailed in Section 3, which introduces the experimental investigation in full. Section 4 sums up some of the most relevant findings.

2. THEORETICAL UNDERPINNINGS

As previously stated, the dual-environment rifle is capable of operating in both water and air environments. When shooting in the air, overpressure can be calculated via a mathematical model[4,8-9] a computational fluid dynamics model[2-3,10] and an experimental approach[5]. Besides, when shooting in the air, the pressure change on the barrel muzzle as a function of time is determined by the following Eqn.

$$p(t) = p_p e^{-Kt} \tag{1}$$

where p_p is the initial pressure, K is the empiric coefficient for barrel, and t is the time.

The following Eqn.[16] is often used to estimate the shock wave pressure associated with an underwater explosion.

$$p(t) = p_{\max} e^{-\frac{t}{\theta}} \tag{2}$$

in which $p_{\max}$ is the peak shock wave pressure, θ is the exponent time constant. It depends upon the mass and type of explosive material and the stand-off distance r.

Alternatively, the Rayleigh-Plesset equation, on the other hand, is frequently used to explain the dynamics of a spherical isolated bubble in terms of bubble radius[21-24]. The Rayleigh-Plesset Eqn.[18] can be expressed as the following equation:

$$R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 + \frac{4\nu_L}{R}\frac{dR}{dt} + \frac{2\gamma}{\rho_L R} + \frac{\Delta P(t)}{\rho_L} = 0 \tag{3}$$

where ρ_L is the density of the water, $R(t)$ is the radius of the bubble, ν_L is the kinematic viscosity of the water, γ is the surface tension of the bubble-water interface, $\Delta p(t) = p_\infty(t) - p_B(t)$, in which, $p_B(t)$ is the pressure within the bubble, and $p_\infty(t)$ is the external pressure infinitely far from the bubble.

Supercavitation is used to keep underwater bullets from exploding (Fig. 1). Previous research has exclusively focused on the supercavitation phenomenon of underwater projectiles[25] or the underwater internal ballistics of underwater projectiles[26] for the underwater shot. However, the dynamics and overpressure of gas bubbles have not yet been investigated.

The goal of this study is to figure out the overpressure of the muzzle blast and how gas bubbles move when shooting underwater. This will be done by doing experiments and giving an explanation.

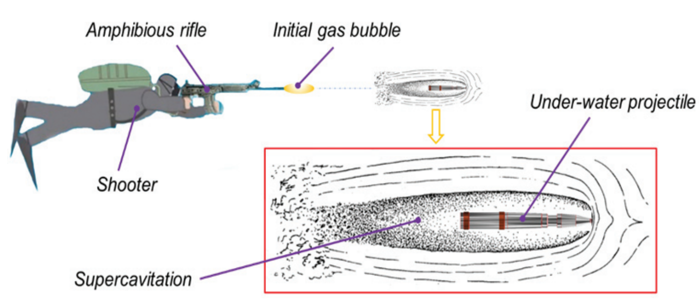

Figure 1. Scheme of the underwater shoot.

3. EXPERIMENTAL STUDY

3.1. Experimental Equipment

The study subject was a 5.56 mm amphibious rifle, which was examined in a water tank over the course of the experiments. This operation used 5.56x45 mm underwater ammunition with a propellant mass of 0.7 g. The shooting takes place at a depth of one meter. The amphibious rifle is secured on the mount with the assistance of the shooter. The experimental setup is shown schematically in Fig. 2.

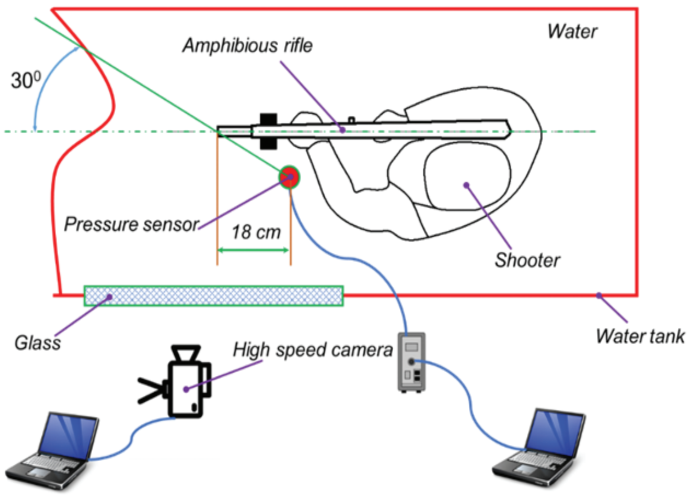

Figure 2. Setup for measuring overpressure and gas bubbles in an experimental environment.

The experiment employs the Photron FASTCAM SA1.1 high-speed camera system[27] to view the gas bubble phenomena (Fig. 3). TEMA was the data analysis software tool utilised.

The underwater overpressure was determined in this investigation utilising a PCB Piezoelectric Pressure Sensor model 138A26[28] and data was gathered using DEWESOFT. PCB Piezoelectric Pressure Sensor model 138A26 is a voltage-mode tourmaline sensor designed for operation underwater or in liquids. In particular, this pressure sensor is used by the military for underwater explosive testing with a resolution of 3.5 kPa. Besides, this sensor is ideal for monitoring dynamic pressures because they exhibit near non-resonant responses[28]. The distance between the muzzle barrel and the sensor location is 18 cm, and the angle between the barrel axis and the muzzle-sensor line is 30^0. The experiment setup is shown in Fig. 4.

Figure 3. Experimental setup for capturing and analysing the gas bubble.

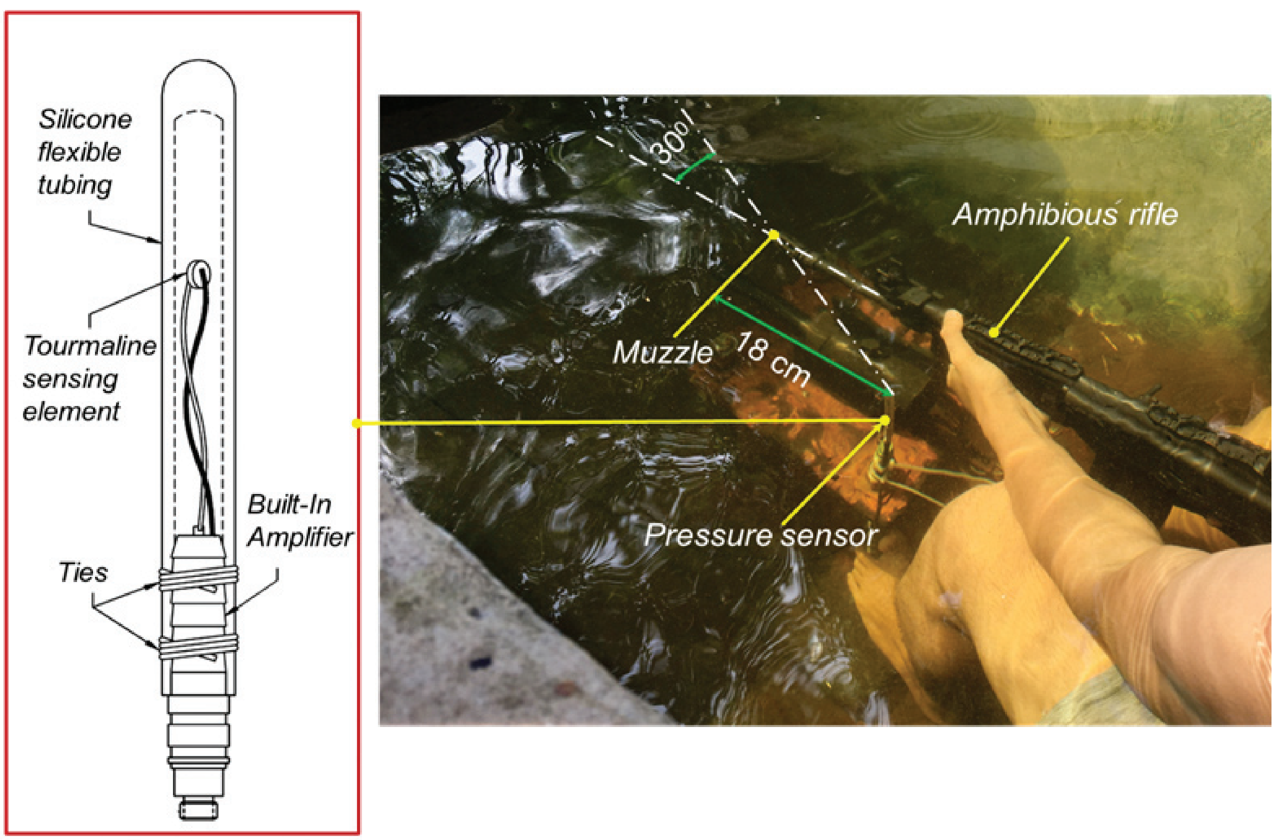

Figure 4. Experimental setup for measuring the overpressure.

3.2. Experimental results

3.2.1.Gas Bubble

Table 1, Figures 5 and 6 show how the radius of a gas bubble has changed over time as shown in the figures. Photographs of the gas bubble show that it has taken on a near-sphere shape and has moved away from its original location.

On the other hand, it is clear that the distance that separates the two places is not very significant. While moving from one bubble maximum to the next, there is a space of 52 millimeters that separates the first bubble maximum from the second bubble maximum. The center of the bubble moved about 113 millimeters further from the muzzle in the horizontal direction at the instant in time when the initial bubble maximum was obtained, as can be seen in this plot, as can be seen in the figure that came before it.

3.2.2.Overpressure

The observed overpressure histories that were acquired from the measurements are shown in Fig. 7. Based on Fig. 7, it is possible to make the observation that the overpressure increases at a lightning-fast rate, reaching a peak of 78.58 kPa before beginning a precipitous decline. During the instant in time when the overpressure is at its highest point, which is very close to the point in time when the bullet leaves the muzzle of the barrel. The pressure goes up and down as the amplitude of a damped oscillation moves into the next stage and goes through its cycle of increasing and decreasing.

3.3. Discussions

3.3.1.The Gas Bubble Characteristics

At first, by following the passage of the gas through the barrel muzzle, as seen in Figs. 5 and 7, a gas bubble starts

Table 1. The radius of the gas bubble at the selected times

	Time (s)	Radius of bubble (mm)	Ratio of bubble radius and barrel caliber	Distance to muzzle (mm)
Initial bubble	0.00261	5.6	1	0
First bubble maximum	0.01249	80.3	14.45	113
First bubble minimum	0.02111	36.9	6.63	134
Second bubble maximum	0.02912	57.6	10.35	165
Second bubble minimum	0.03509	41.9	7.54	194

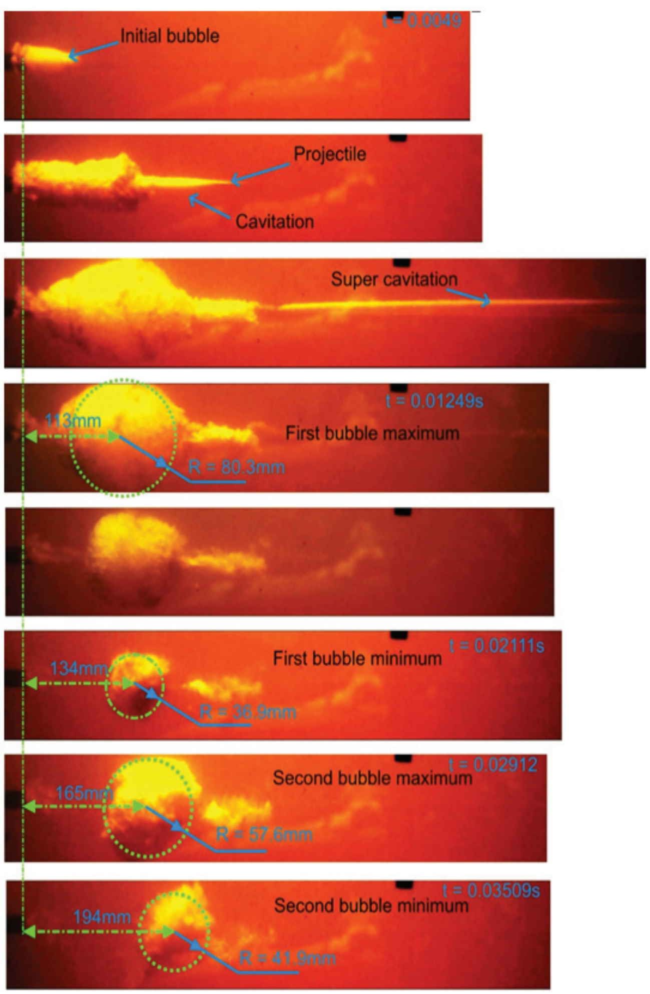

Fig. 5. The gas bubble changes as a function of time.

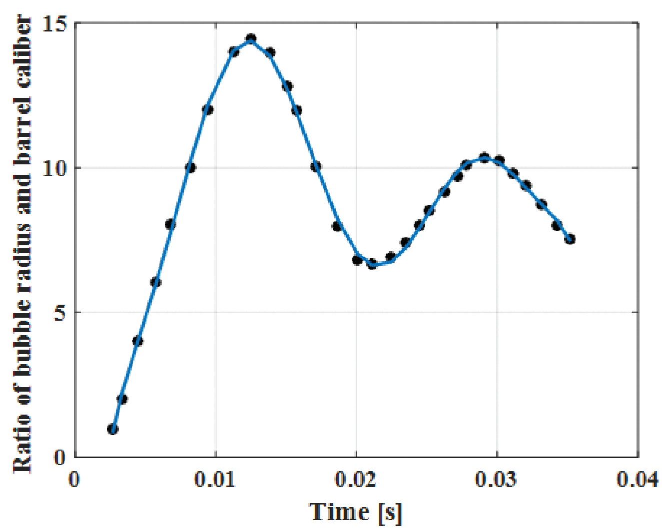

Figure 6. Ratio of bubble radius and barrel caliber change as a function of time.

to grow radially outward as a result of the high temperature and pressure generated by the propellant gas byproducts. Because the pressure within the bubble is higher than the pressure outside the bubble, the gas bubble continues to grow radially outward. Without a doubt, the bubble will eventually reach a point in time at which all of the pressures within and outside of the bubble are equal, but because of the considerable outward velocity of the bubble, it will continue to expand radially outward indefinitely. When the bubble reaches its first bubble maximum, the overpressure is low while the pressure within the bubble is high. This is known as the first bubble maximum. In the related pressure-time history, this is reflected as a long-duration negative pressure phase, which persists for the majority of the time period of the bubble oscillation and lasts for a lengthy period of time. The bubble is now in the process of contracting, swiftly passing past the point of pressure equilibrium and continuing to recompress the gaseous components of the bubble. The contraction of the bubble continues until the bubble is unable to contract anymore owing to the compressibility of the gases contained inside it. At this point, the bubble suddenly stops shrinking inward. This causes the first bubble pulse, which can be seen in the related pressure-time history.

Following that, Fig. 8 is the illustration of the relationship between bubble size and pressure.

As the bubbles expand, shrink, and pulsate, it can be seen that the operation is repeated. For each of the subsequent oscillations, the maximum bubble diameters become progressively smaller (the radius bubble maximum of the first bubble is 80.3 mm, and the radius bubble maximum of the second bubble is 57.6 mm), while the minimum bubble diameters at pulsation become progressively larger (the radius

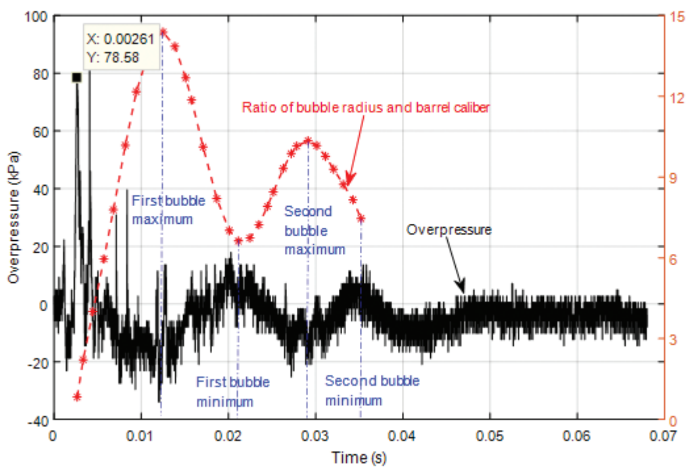

Figure 7. Overpressure and the ratio of bubble radius and barrel caliber change as a function of time.

bubble maximum of the first bubble is 80.3mm, and the radius bubble maximum of the second bubble is 57.6mm, the radius bubble minimum of the first bubble is 36.9mm and the second bubble is 41.9 mm). The pressure-time history associated with the negative pressure and bubble pulse is also evident in the subsequent phases of the experiment. The magnitude of each of these pressures diminishes with each subsequent pulse.

Next, when solving for the ratio of bubble radius to barrel caliber from Eqn. (3), the graph is shown in Fig. 9 is obtained, which shows the change in the ratio of bubble radius to barrel caliber over time.

A gas bubble's size may be described and quantified using the Rayleigh-Plesset Eqn.[21-24], based on the experimental data shown above. Using the assumption that the gas bubble's initial radius (R_0) is 5.56mm (equivalent to the caliber), and that the beginning pressure is equal to the gas pressure at the time the bullet leaves the barrel.

Finally, it is clear from the comparison of the mathematical result and the experimental data that the rule of change in the size of a gas bubble is perfectly consistent (Fig.10).

The comparative findings shown in Fig. 10 allow us to draw the following conclusion: The Rayleigh-Plesset Eqn. may be used to calculate the size of the gas bubble that will be used for the underwater recording that will take place.

3.3.2. Change Law of Overpressure

As a consequence of the experimental findings (Fig. 7), the following equation may be used to forecast the changing law of overpressure for the underwater shooting situation.

$$p = p_0 e^{-At} Cos(\mathrm{t}) \tag{4}$$

where p_0 is the peak shock pressure, A is the constant.

In this paper, the application of Eqn. (4) to the amphibious rife is examined, and the changing law of overpressure can be noticed as shown in Fig. 11.

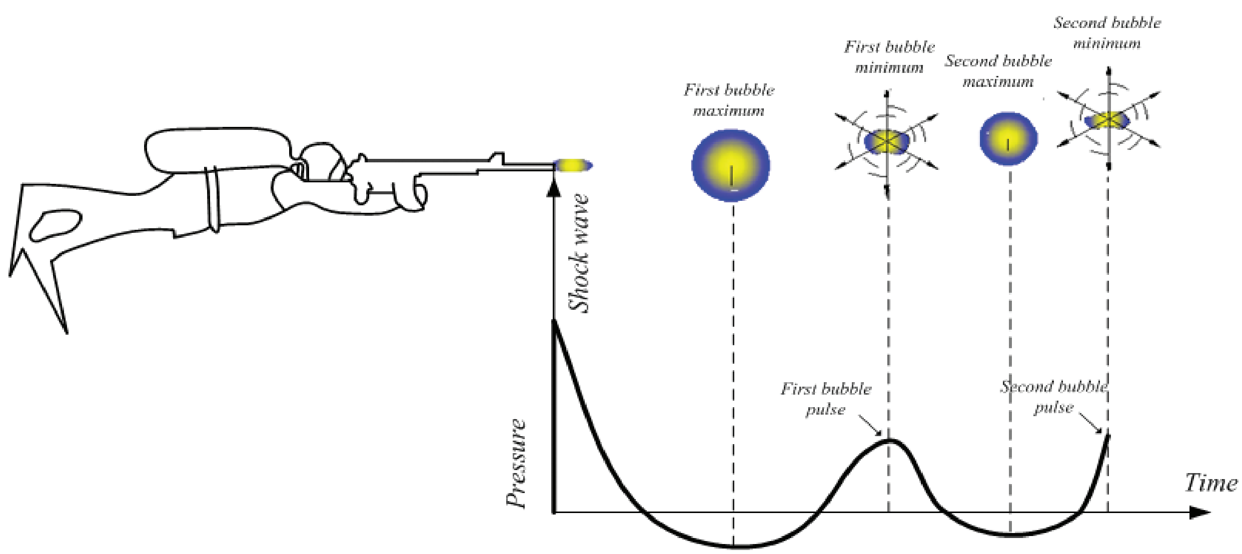

Figure 8. The relationship between bubble size with overpressure vs time.

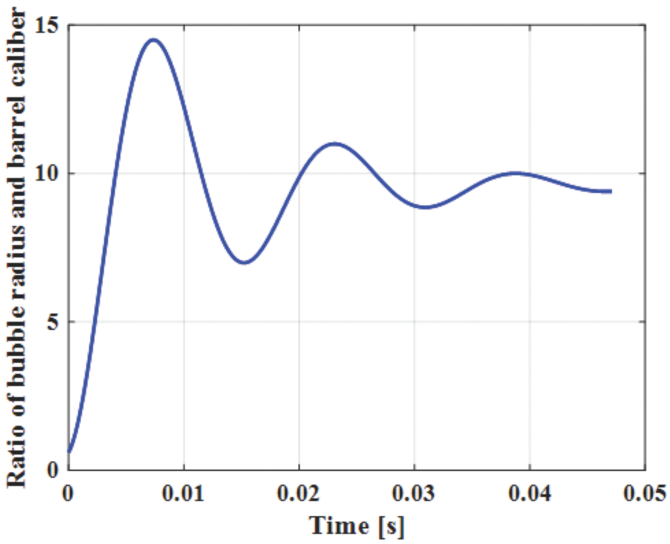

Figure 9. Calculation results in the change of the ratio of bubble radius and barrel caliber vs time.

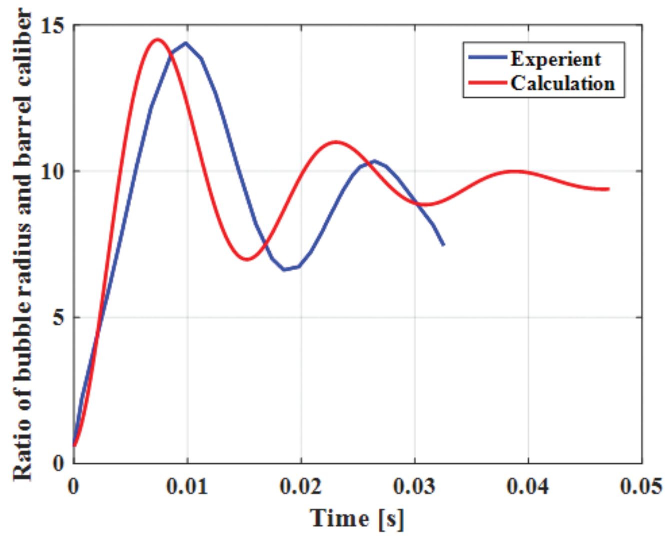

Figure 10. Comparison of the ratio of bubble radius and barrel caliber between theory and experiment.

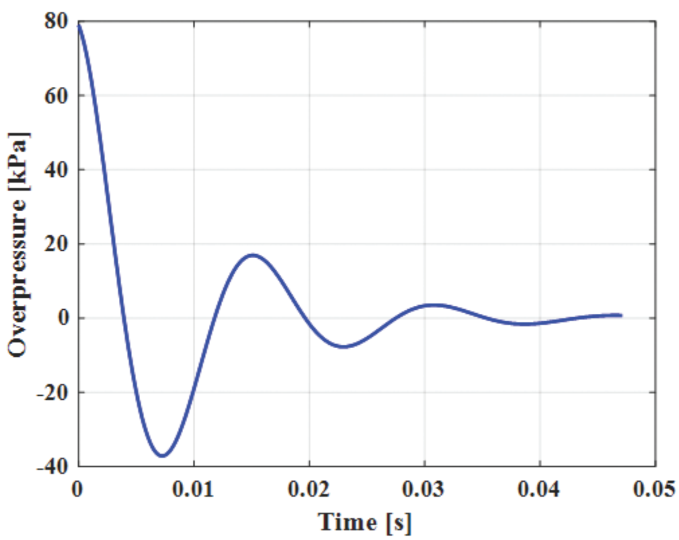

Figure 11. Calculation results in the change of overpressure vs time.

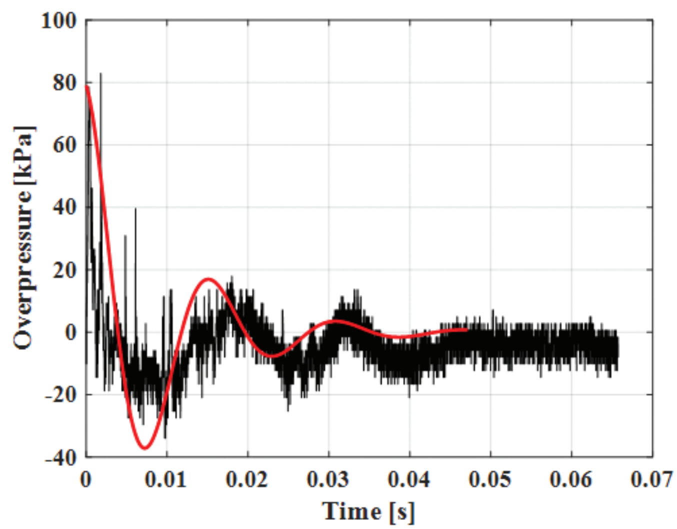

Figure 12. Overpressure comparison between theory and experiment.

It can be shown from a comparison of the calculation result and the experimental findings that the law of change of overpressure is perfectly consistent (Fig. 12).

4. CONCLUSIONS

Muzzle blast is a difficult phenomenon in underwater shooting, and it may be determined by experiment in the present study. The experimental examination is carried out for 5.56 mm amphibious rifles when they are used to fire underwater with a 5.56 mm underwater projectile, and the results are presented. Based on the analysis that was performed, the following conclusions may be derived from the results of the tests.

(1) When firing underwater with an amphibious rifle, the Rayleigh-Plesset equation may be used to describe and determine the size of the gas bubble created by the weapon.

(2) The Eqn. (4) can be used to figure out how the overpressure will change during the underwater shoot.

The experimental procedure presented in this work provides an efficient way for determining the change law of the gas bubble and overpressure for the amphibious rifles when they are used to shoot underwater with their ammunition. This method can give you a powerful tool for making underwater weapons and rifles that can be used on land and water. It can also help you figure out how underwater muzzle blasts are made..

The muzzle blast, on the other hand, is impacted by a variety of factors, including the underwater shooting environment and the design of the muzzle device. The theoretical and experimental results of this paper play a very important role. In the future, researchers might look at how the characteristics of gas bubbles and overpressure affect the shooter in different situations, such as when shooting underwater or with different muzzle devices.

This paper's findings are critical to our knowledge of how air bubbles arise when a gun is discharged under water. It may be used as a starting point for underwater weapon research, computation, and design in the near future.

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In the current study, he carried out the literature review, performed the experiments, analyzed the experiment data, and revised the manuscript based on the reviewer's comments.

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In the current study, he analyzed the experiment data and contributed to writing the manuscript.