Study on interaction characteristics between multi gas jets and water during the underwater launching process

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ABSTRACT

To further understand the mechanism of new submerged water piercing gun launcher, the simulation device of an imitated projectile is designed with using multi combustion gas jets to drain off the water in gun tube. The expansion characteristic of multi gas jets and generation mechanism of the gas-curtain in the liquid medium are experimental observed by a high speed camera. The experiment shows that, with the mixing process between the multi combustion gas jets and the liquid medium, the gas-curtain is generated, which provides a gas path for the projectile motion. On the base of experimental observation result, the influences of injection pressure and sprayer structure on projectile motion are discussed. Experiment result indicates: increasing injection pressure, both axial expansion velocities of gas-curtain and projectile moving speed increase; magnifying the center nozzle cannot enhance the drainage performance of the gas-curtain and will restrain projectile motion in the later stage; with enlarging the oblique plane nozzles, the axial velocity of gas-curtain tend to rise after converging and projectile kinematic performance is also improved.

Key words: multi combustion-gas jets; gas-liquid interaction; gas-curtain generation; experimental study; underwater gun launcher

1. Introduction

Kinetic resistance of underwater vehicles can be greatly reduced with the supercavitation technology, which has brought enormous development potentiality for underwater launching ^[1]. However the two traditional underwater gun launchers, the sealed launcher ^[2] and submerged launcher ^[3], have some limitations in practical application. The sealed launcher, which has a higher muzzle velocity, requires a complex muzzle sealing structure. The submerged launcher, of which the launching system is relatively simpler, has a lower muzzle speed. This is because the resistance of underwater moving projectile is almost 800 times of that in the air.

Fig.1 Sketch of the water piercing launcher

The water piercing launcher is a new concept of underwater launching missile, which can effectively reduce movement resistance. Fig.1 shows the sketch of the water piercing launcher, the working principle of which is employing a concentric canister launcher to create a gas path for the moving missile. During the launching process, the combustion gas is generated by the engine and flows into inner cylinder. Then, flowing through the hemisphere, the gas enters into the outer cylinder. As the velocity of the combustion gas is much faster than missile, it will reach to the external environment before the missile and generates a gas path. Experiment result shows^[4] that both launching velocity and depth can increase with the water piercing launcher.

There are some researches on the gas-liquid interaction during underwater launching. The gas-liquid interface generated with the water piercing launcher is experimentally captured by Yagla^[5], and gas-liquid interaction characteristics during the launching process is numerically discussed^[6, 7]. Through numerical simulation methods, Cao Jia-yi^[8, 9] acquired the variation characteristic of gas boundary and inner flow field during the underwater launching process. Liu Haijun^[10] numerically analyzed the influence of missile velocity on missile loading characteristics, and the influence of gas elasticity is also considered by Wang Yadong^[11].

Despite research of the water piercing launcher is mainly concentrated on underwater missile launch; the working principle provides a new method for underwater gun launcher. Unlike the missile launcher, the gas path of the gun launcher should be generated in the gun tube, the interaction between the combustion gas and liquid medium is in a limit space. In this respect, QI

^[12] and Mang ^[13] experimental and numerical studied the shape characteristic of single jet in flat liquid chamber and step cylindrical liquid chamber. On this base, the expansion characteristics of twin gas jet have been discussed in a flat chamber by Yu^[14]. Xue^[15,16] analyzed the interaction between the twin jets in cylindrical chamber and the effect of the injection structures. And dynamics characteristics in the merging process of the four gas jets in water chamber is experimental discussed by Graaf^[17].

Based on the background of the water piercing launcher, the simulator of underwater gun is designed. The interaction process between multi jets and liquid medium is experimentally captured with the motion of projectile.

2. Experimental setup

Fig.2 shows the structure of simulation experimental system and the device picture is shown in Fig.3, which is composed of the combustor, the water-filled tube and the moving sprayer (the imitated projectile). The combustor contains ignition charge, including fast-burning powder and particle propellants. The fast-burning powder is made up of Nitro-cotton powder, and the particle propellants are 1/2 single-base gunpowder. For easy observation, the tube is constructed of transparent organic glass, of which the diameter is 20mm and the length is 1m. As is shown in Fig.4, the sprayer consists of 9 nozzles, including 1 center nozzle, 4 oblique plane nozzles and 4 rectangular nozzles in the side wall. To discuss the influence of nozzle size, 3 different sprayers are designed, the structure parameters are presented in Table 1.

1. Water-filled tube 2. Sprayer 3. Seal film 4. Connector 5. Charge 6. Ignition electrode

7. Combustor 8. Pressure sensor

Fig.2 Diagram of the experiment system

Fig.3 Picture of the device

1. Rectangular orifice 2. Center orifice 3. Oblique plane orifice

Fig. 4 Structure of the sprayer

Table 1 Geometry size of the sprayers

Type	Center nozzle diameter Φ_1 /mm	Oblique plane nozzle diameter Φ_2 /mm	Side wall rectangular nozzles/mm
A	1.5	1.5	3×1
B	2	1.5	3×1
C	2	2	3×1

The working principle of the simulator is employing combustion-gas to create a gas path in gun tube for the moving sprayer. When the ignition circuit is switched on, a pulsed electrical current is produced and passes through the ignition electrode that ignites the ignition charge. Then high-temperature gas is continually generated and the pressure in the combustor increases dramatically. When the pressure reaches to the preset value, seal film in the sprayer is broken; the multi combustion gas-jets are injected into the water-filled tube. With turbulent mixing between multi jets and liquid medium, the gas curtain is generated and creates a gas path in the tube. At the same time, the connector between sprayer and combustor is also broken; the sprayer is driven to move in the gun tube.

During the experiment, the injection pressure is monitored by a Kister piezoelectric transducer; and evolutionary process of the multi gas jets is recorded by the FASTCAM-Ultima APX high-speed digital camera, of which maximum resolution is 1024×1024 pixels and frequency is 2000 frames/s.

3. Expansion observation of launching process

Fig.5 shows the p - t curve in the combustor under a typical condition, and Fig.6 shows the corresponding launching process. The sprayer used in this condition is the A type sprayer.

Fig.5 p - t curve of A sprayer ($p_{\max}=4.4\text{MPa}$)

As Fig.5 shows, after ignition, pressure quickly reaches the peak value that is $p_{\max}=4.4\text{MPa}$. With injection of gas jets, the remaining gas in the combustion decreases and the injection pressure drops.

Fig.6 The expansion process of multi combustion-gas jets with sprayer movement

($p_{\max}=4.4\text{MPa}$, A sprayer)

During the launching process in Fig.6, the multi jets are independently injected into the liquid medium before 1ms, and expand along the nozzle directions at the beginning. At $t=1.5\text{ms}$, the 4

oblique plane jets contacts with tube wall and expansion direction changes. Then with axial expansion of the 4 side wall jets, they merge with the oblique plane jets that form the 4 side jets. At $t=2\text{ms}$, the side jets are formed on the tube wall, and the center jet is extruded that a protuberance arises in the center. At $t=4\text{ms}$, the center jet merges with the side jets, the gas-curtain is generated. After the generation of gas-curtain, it expands along the axial direction and forms a gas path in the tube.

According to photographs in Fig.6, the mean axial expansion velocity can be acquired from the displacement of gas-curtain, as shown in Fig.7. Combined with Fig.6, it can be found that, at the very beginning, the high-pressure gas jet rushes into the liquid at a high speed. The center jet is at the front of multi jets, which supplies most of energy for driving the water. In this stage, the expansion velocity characteristic is familiar to the single jet. The farther the jet strikes from the nozzle, the less remaining energy and smaller expansion velocity it takes in. Therefore, the expansion velocity declines sharply before $t=3\text{ms}$. Then with the merging of the gas jets, axial extension capacity of the center jet of the center jet is enhanced, and the velocity decreasing rate slows down. After $t=8\text{ms}$, with the generation of gas-curtain, liquid medium is driven by the gas-curtain and the velocity gradually rises. As injection pressure drops to a lower value after $t=12\text{ms}$, the upward trend of expansion velocity slows down

Fig. 7 The axial velocity of multi jets front end

Fig. 8 The v - t curve of sprayer in the tube

The mean velocity of sprayer also can be obtained, which is shown in Fig.8. As turbulence mixing occurs between gas jets and the liquid medium during the generation process of gas-curtain, resistance to the sprayer drastic changes at the initial stage. It can be seen that sprayer velocity rises with fluctuation trend before $t=18\text{ms}$. Before $t=3\text{ms}$, the sprayer velocity constantly increases, but the rising rate decreases with dropping of injection pressure. During $t=3\text{--}5\text{ms}$, mixing interaction occurs between the multi jets, and pressure in the Taylor cavities increases, which enlarges resistance on the sprayer. In this stage, the velocity rising rate instantaneously decreases. After generation of gas-curtain, pressure inside the Taylor cavities drops and the resistance on the sprayer also decreases. Therefore, during $t=5\text{--}9\text{ms}$, the velocity rising rate shows an upward trend. As the quantity of combustion gas is limited, pressure continues to decrease during sprayer moving process and the sprayer acceleration process also slows down after $t=9\text{ms}$. Finally, the thrust is close to the resistance, the acceleration of the sprayer towards zero. As the figure shows, sprayer velocity basically remains the same after $t=18\text{ms}$, which is nearly 5.8m/s .

4. Experimental study on the influence of the injection parameters

In the experiment, different injection pressure and different sprayers are used to compare the influence of injection parameters on launching process.

4.1 Influence of injection pressure

Contrast experiment on injection pressure is conducted with the A sprayer, and the injection pressures are 4.4MPa and 7.4MPa respectively. Comparison of gas-curtain axial expansion velocity is shown in Fig.9, corresponding sprayer speed is shown in Fig. 10.

Fig.9 Axial velocity of multi jets under different pressure

As shown in Fig.9, with the increasing of injection pressure, Rayleigh-Taylor instability at the top of the gas-curtain is enhanced and the axial expansion velocity of the gas jet also increases. During the expansion process, the energy dissipation rate of the gas jets also rises, and the velocity decay rate is accelerated. The magnified mass flow increases the amount of gas in the Taylor cavities that enhances the gas aggregation during the merging process. In consequence, the turning point of velocity curve is 3ms earlier and the rising rate also increases. The final axial expansion performance of the multi jets is improved after the generation of gas-curtain. The injection pressure rises from 4.4MPa to 7.4MPa; the expansion velocity increases by 3m/s.

Fig. 10 The v - t curve of sprayer under different pressure

In consequence of advanced discharging performance of the gas-curtain, the kinematic performance of the sprayer is improved under 7.4MPa. As Fig.10 shows, velocity of B sprayer reaches to 9.3m/s at $t=20$ ms, which increases by 58%.

4.2 Influence of center nozzle size

Contrast experiment on center nozzle is conducted with the A sprayer and B sprayer under

the pressure of 7.4MPa. On the base of A sprayer, center nozzle diameter of B sprayer increases to 2mm, the area of flow channel rises by 77%. Difference between gas-curtain velocities is shown in Fig.11.

Fig.11 The v - t curve of multi jets with different center nozzle diameter

As the figure shows, due to the added gas flow in the center jet, expansion velocity of B sprayer gas jet is increased at the beginning. The raised expansion velocity also enhances the instability of the gas-curtain; the expansion velocity is more volatile in the later stage. However, during expansion process, energy of center jet dissipates, and axial transport of center jet is restrained. Finally, the expansion velocity of B sprayer gas-curtain approaches to A sprayer.

Fig.12 The v - t curve of sprayer with different center nozzle diameter

The increasing gas flow also accelerates the pressure dropping process in the combustor, and the thrust relatively decreases. As shown in Fig.12, at the beginning, sprayer moving velocity of B sprayer is lower than of A sprayer. As time goes on, the larger moving velocity of A sprayer induces the higher growing rate of gas chamber. Therefore, the injection pressure in the combustion chamber drops faster and velocity rising rate decreases. The final moving velocity of the two sprayers is very close. It can be seen that, despite the gas flow increases in the center of B

sprayer gas-curtain, kinematic performance is not improved.

4.3 Influence of oblique plane nozzles size

The influence of oblique plane nozzles is experimentally discussed between B sprayer and B sprayer. On the base of B sprayer, diameter of oblique plane nozzles in C sprayer is increased to 2mm. According to the contrast experiment under the pressure of 7.4MPa, expansion velocity of the gas-curtain can be obtained, as is shown in Fig.13. And Fig.14 compares the variation of sprayer velocity.

Fig.13 The v - t curve of multi jets with different oblique plane nozzle diameter

Compared with the velocity of the gas-curtain generated by B sprayer, expansion velocity fluctuation of C sprayer gas-curtain is restrained, and velocity rising rate increases after the merging process. As the figure shows, the drainage performance of C sprayer gas-curtain is improved after $t=10$ ms.

Fig.14 The v - t curve of sprayer with different oblique plane nozzle diameter

As Fig.14 shows, moving velocity of C sprayer is increased to 10.6m/s at $t=20$ ms, which is 23% higher than B sprayer velocity. It can be found that the kinematic performance of sprayer C is improved during the launching process. This is mainly because the enlarged oblique plane nozzles

enhance turbulent mixing near tube wall that promotes the drainage property of the multi jets. With enhanced drainage performance, the gas volume fraction also increases on the C sprayer surface and moving resistance of the sprayer is decreased.

5. Conclusion

Based on the research results of this paper, the following conclusions can be obtained:

(1) Experiment photograph shows, gas-curtain can be generated with the mixing process between multi combustion gas jets and the liquid medium that provide a gas path for the moving sprayer.

(2) Increasing injection pressure, the mixing process is enhanced at the beginning; both gas-curtain expansion velocity and sprayer speed are increased after the merging of gas-curtain.

(3) With enlarged center nozzle, gas flow is increased in the center jet; but the drainage property of the multi jets and sprayer kinematic performance are not improved.

(4) The diameter of the oblique plane nozzle increase from 1.5mm to 2mm, the moving velocity of sprayer is increased by 23%, and the expansion velocity rising rate is also increased. The gas-curtain is enabled with better water drainage property at the later stage and the sprayer kinematic performance is also improved.

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