Main Characteristics of Underwater Supersonic Gas Jet Flows

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Received 4 January 2022; Accepted 23 April 2022; Published 31 May 2022

Academic Editor: Mostafa S. Shadloo

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Underwater supersonic gas jet flows are sophisticated physical phenomena that widely exist in underwater propulsion, such as underwater rocket, high-speed torpedo, and water-piercing missile launcher (WPML). The present study aims to explore the characteristics of underwater supersonic jets. This research carries out two-dimensional and three-dimensional underwater jet experiments and establishes an improved spherical bubble model to study the transient and steady-state characteristics of the underwater supersonic jet. The simulation results show that the entrainment strength and anti-interference ability are the main factors affecting the transient characteristics of underwater supersonic jets. The experimental results show that the jet angle increases with increasing pressure and the increased rate of the jet angle decreases with increasing pressure. The jet pulsation exists in the entire experimental pressure range from 0.4 MPa to 6.5 MPa. The frequency of back-attack increases first and then decreases with increasing pressure in the chamber. The frequency peak appears at 0.8 MPa, which is 5.96 Hz.

1. Introduction

Submerged gas jets are widely existing in underwater propulsion, submarine launch of missiles, and underwater artillery launching. When the gas is injected into the liquid at a high speed, complex interactions occur at the interface, causing the pulsation and back-attack of the jets. The propulsion system and the launch platform are affected by the instability of the jets. Therefore, understanding the characteristics of submerged gas jets is significant to reduce their adverse effects.

The phenomenon in which submerged air jets in mercury penetrates extensively behind the nozzle was observed in experiments by Oryall and Brimacombe in 1976 [1]. The submerged gas jets in water blown back were found and the concept of back-attack was proposed by Aoki. Aoki analyzed the mechanism and pointed out that the back-attack event is caused by the suction of the jet [2]. Loth and Faeth conducted a lot of theoretical and experimental studies on submerged turbulent air jets and found out that with the increased flow rate, the stability of jet increases, and the development of jet slows down [3, 4]. Submerged horizontal gas jet has larger back-attack intensity because of buoyancy. The frequency and intensity of the back-attack effectively decrease with the rotating horizontal gas jet [5]. By researching the submerged combustion system, the critical Weber number has been put forward to divide the gas jet into bubbling regime and jetting regime, and the coupling of jet instability and pressure fluctuation in the chamber has been found [6–8].

Many experiments show that the submerged jet instability has two models, pulsation and back-attack, in which the frequency of pulsation is distributed from 0 Hz to 300 Hz [9], and the frequency of back-attack is about 10 Hz [10, 11]. Self-similarity feature of the submerged jet was proved by measuring the steam injection using the PIV measurement technique [12]. Weiland and Vlachos found that the pinch-off occurs at the intensity of the location where the turbulence intensity reaches a peak [13]. Harby et al. pointed out that the nozzle diameter and Froude number play an important role in determining the pinch-off and jet instability, and Froude number also influences the angle and half-width of the jet [14, 15]. Syeda and Ansery’s study proved that the jet length is linear with Mach number and the viscosity of fluid influences the development of jet compared with three kinds of liquid [16]. Qin et al. revealed that the pressure ratio has a great influence on the diameter of the jet [17]. Based on the dimensional analysis and the data from
submerged steam jet experiments, Zhang et al. proposed a semiempirical formula to predict the length of penetration, which shows that the density ratio, gas velocity, and nozzle diameter influence the length [18]. Peng et al. studied the submerged cavitation jet, analyzed the spectral characteristics of the cavitation cloud’s high-speed photography characteristic signal, and observed the existence of the stable-frequency zone of the cavitation cloud shedding [19].

Recently, numerical simulation has become a powerful tool to study this issue. Wang and Zhang used the spherical bubble model to study the flow status and underwater thrust [20]. The shock wave structure of the submerged gas jet and the bubble in water has been simulated [21]. Cheng and Liu’s simulation revealed that the bubble of the submerged gas grows rapidly along the axial direction and the necking pheromone finally occurs [22]. Tang and Li established the simulation model by using the volume of fluid (VOF) method to explore the characteristics of the submerged rocket. The main phenomena, including expansion, bulge, necking, breaking, and back-attack, can be observed. The results showed that the thrust pulsation is caused by the pulses of the back pressure and the nozzle exit pressure [23–26]. Through simulating different various liquid densities of liquid, Fronzeo and Kinzel disclosed that the jet tends to lose stability, shortens the length of penetration, and heightens the turbulence intensity and the frequency of back-attack. The frequency also increases with the liquid density [27]. Xue et al. established a three-dimensional mathematical model based on the experiments to explore the expansion characteristics of combustion gas jet in liquid. The results showed that the Kelvin–Helmholtz instability plays an important role in the interactions between gas and liquid [28]. Gong et al. studied the effect of depth on thrust characteristics and pointed out that jet stability decreases as the depth grows [29]. The submerged jet with a rectangular nozzle was studied by the CFD method, which revealed the effect of nozzle cross section shape and two low-frequency oscillations can be found that are caused by necking and back-attack. With the increase of pressure, two distinct flow regimes appear. At low pressure, the flow regime is similar to the round nozzle. And with the increase of pressure, the cross-like cross section jet gas/water boundary started to form [30]. Huang et al. established the small perturbation equation accounting for the gas concentration distribution and analyzed the linear stability of underwater supersonic gas jets [31]. Jana and Sucheendran studied the difference of flow field structure between underwater jets and air jet and analyzed the influence of Mach number and stagnation pressure on jet vibration and flow field characteristics [32]. Zhang et al. studied the evolution process of the underwater jet interface and pointed out that K-H instability plays a leading role at the outlet of the nozzle, while R-T instability dominates downstream due to buoyancy [33].

Recent research focuses mainly on the initial stage of the jet flow. The present study aims to discuss the transient and steady-state characteristics of the underwater supersonic jet. Therefore, an experiment of underwater thrust pulsation characteristics has been carried out, and an improved spherical bubble model is established considering the gas outflow from the spherical bubble.

2. Experiment Methods

2.1. Experiment Device and Test System. Figure 1 is the diagram of the experiment device. The main components of the device are the thrust measuring apparatus, the poly-methyl methacrylate (PMMA) experimental tank, and the gas supply system. The thrust measurement apparatus is fixed at the bottom of the experimental tank. A compressed air cylinder is used as the gas supply device controlled by the electromagnetic valve.

Figure 2 shows the experiments test system. A PCB 208C02 force sensor and a CGY1401 pressure transducer are employed to measure the underwater jet thrust and pressure in the chamber, respectively. A high-speed camera, Phantom Miro M310, records the underwater jet shape at 1000 fps with a shutter speed of 4 us. The resolution of the recorded images is $640 \times 480$ pixels.

2.2. Experimental Conditions. Figure 3 demonstrates the geometry of the three-dimensional nozzle, in which the throat diameter is 4 mm. A cylinder can be exploited for four experiments, and the gas supply time of each experiment is 25 s. The stagnation pressure in the chamber is shown in Figure 4.

Figure 5 shows the geometry of the two-dimensional nozzles. The throat of the two-dimensional nozzle is rectangular which is $4 \times 13$ mm. The mean pressure in the chamber is 0.189 MPa, and the pressure versus time curve is shown in Figure 6. A two-dimensional jet region of $530 \times 300 \times 13$ mm is formed by installing two pieces of PMMA baffle board at the nozzle exit, as shown in Figures 7 and 8. Since the jet can fill the gap between the two baffles, the jet formed in the area between the baffles can be approximately considered as a two-dimensional jet.

2.3. Uncertainty Analysis. For the PCB208C02 force sensor, the measurement range is $\pm 444.8$ N. The maximum static compression force is 2.669 kN, and the maximum static tension force is 2.224 kN. The sensitivity is 11.15 mV/N. The error of sensitivity is $\pm 1\%$. The nonlinearity is lower than 1%; the temperature coefficient of sensitivity is lower than
Based on the data in the manual, the overall uncertainty of PCB208C02 force sensor is 15.06%.

For the CGY1401 pressure transducer, the measurement range is 25 MPa. The sensitivity is 0.1996 V/MPa. The error of sensitivity is 0.363%. The nonlinearity is 0.28%. The repeatability error is 0.04%. The hysteresis error is 0.06%. Based on these data, the overall uncertainty of CGY1401 pressure transducer is 0.46%.

3. Theoretical Methods

3.1. Improved Spherical Bubble Model. To simulate the long-term thrust characteristics, the improved spherical bubble model considering mass outflow has been proposed. The following assumptions are made in the modeling:

(1) There is an apparent interface between the gas and water and no mass transfer at the interface
(2) The bubble generated at the nozzle outlet has a spherical bubble shape, regarded as an equal pressure bubble
(3) The viscosity and surface tension of the environment medium are ignored due to the large Reynolds number and Weber number at the nozzle exit

Based on the experimental result shown in Figure 9(a), the basic structure of the spherical bubble model considering mass outflow is proposed, which is mainly composed of the mass inlet determined by the nozzle structure, the spherical bubble, where the radius is \( R \) and the mass outlet channel whose radius is \( r_c \) shown in Figure 9(b). The spherical bubble at the exit of the nozzle, of which the radius is \( R \), is described by the Rayleigh–Plesset equation:

\[
\frac{d^2R}{dt^2} = \frac{p_b - p_{env}}{\rho L R} - \frac{3}{2R} \left( \frac{dR}{dt} \right)^2,
\]

where \( p_b \) denotes the pressure in the spherical bubble.
The energy-conservation relationship of gas in the bubble can be expressed by
\[
\frac{d}{dt} \rho_b V_b e_b = C_p T_0 \dot{m}_{in} - C_p T_{out0} \dot{m}_{out} - p_b \frac{dV_b}{dt},
\]
where \(\rho_b\) represents the gas density in the spherical bubble, \(V_b\) denotes the volume of the spherical bubble, \(e_b\) is the unit volume energy of the spherical bubble, \(C_p\) is the specific heat capacity at constant pressure, \(\dot{m}_{in}\) is the mass flow rate of the gas flowing into the bubble, \(\dot{m}_{out}\) is the mass flow rate of the gas flowing out of the bubble, \(T_0\) is the total temperature of the gas in the chamber, and \(T_{out0}\) is the total temperature of gas flowing out of the bubble.

The mass outlet channel is a hypothetical circular hole, and the mass flow rate of the spherical bubble can be stated as
\[
\dot{m}_{out} = \begin{cases} \frac{r_c}{r_0} \ m_c \ k_m \dot{m}_{in}, & r_0 < r_c < \frac{R}{\sin(\alpha_0)}, \\ \frac{R \sin(\alpha_0 + \arcsin(\frac{r_c}{R}))}{\arcsin(\frac{r_c}{R})} + \alpha_0 < \pi, & r_c + R \tan(\alpha_0), \end{cases}
\]
where \(r_c\) denotes the radius of the hypothetical circular hole, \(r_0\) represents the critical radius of the mass outlet channel, \(m_c\) and \(k_m\) are the parameters of the model, \(\alpha_0\) denotes the half-angle of the jet at \(P_0\), and \(P_0\) is the total pressure in the chamber.

According to Brennen’s method for deriving the Rayleigh–Plesset equation [35], the governing equation of the circular hole is derived. Since the hypothetical circular hole is two-dimensional, which is shown in Figure 10, according to mass conservation, \(u(r, t) = F(t)/r\), where \(r\) is the distance from a point in the liquid to the circular hole center, \(u\)
is radial velocity and $F$ is related to $r_c$ by a kinematic boundary condition at the bubble boundary.

Due to the mass loss along the jet direction in the physical process, the mass loss coefficient $n$ is introduced.

Therefore, the relation of the mass conservation relationship takes the following form: $u(r, t) = F(t)/r^n$.

The influence of spherical bubble size on the mass outlet channel can be expressed as

$$
\frac{d}{dt}\left(\frac{r_c^{n+1}}{R} \frac{dR}{dt}\right) - \frac{1}{\rho_L} \frac{\partial p}{\partial r} + \frac{\partial u}{\partial r} + \frac{\partial u}{\partial r}
$$

Assuming there is no mass transfer through the circular hole boundary, it is easy to get that $u(r_c, t) = dr_c/dt$. The N-S equation, under the condition of spherical symmetry, can be expressed as

$$
\frac{d}{dt}\left(\frac{r_c^{n+1}}{R} \frac{dR}{dt}\right) - \frac{1}{\rho_L} \frac{\partial p}{\partial r} = \frac{1}{(n-1)r_c^n} \frac{dF}{dt} - F^2
$$

where $\rho_L$ is the density of the liquid.

Substituting for $F$ from $u(r, t) = F(t)/r^n$ and integrating the equation to get

$$
\frac{d}{dt}\left(\frac{r_c^{n+1}}{R} \frac{dR}{dt}\right) = \frac{1}{(n-1)r_c^n} \frac{dF}{dt} - F^2
$$

After the application of the condition $p \rightarrow p_{env}$ as $r \rightarrow \infty$, where $p_{out}$ is the pressure in the mass outlet channel and $p_{env}$ is the environment pressure.

Substituting for $F$ from $F(t) = r_n^2dr_c/\rho_L\frac{dt}{dt}$, the expression of the mass outlet channel radius $r_c$ is

$$
\frac{r_c}{n-1} \frac{d^2r_c}{dt^2} = \frac{1}{\rho} (p_{out} - p_{env}) - \frac{n+1}{2(n-1)} \left(\frac{dr_c}{dt}\right)^2 + \frac{r_c^2}{(n-1)R} \frac{d^2R}{dt^2} + \frac{n+3}{2(n-1)} \frac{r_c}{R} \frac{dr_c}{dt} \frac{dR}{dt} - \frac{r_c^2}{(n-1)R^2} \left(\frac{dR}{dt}\right)^2.
$$

The distribution of the underwater pressure field is
where \( p_s \) is the pressure at a distance of \( r_w \) from the center of the spherical bubble.

The underwater thrust is

\[
F_t = m_{in}v_{in} + A_e(p - p_{env}) + \int_{A_e} (p_s - p_{env})dA,
\]

where \( v_{in} \) is the velocity of the gas flowing out of the chamber, \( A_e \) is the area of the nozzle exit, \( A_i \) is the area of the nozzle exit plane excluding \( A_e \), and \( F_t \) is the thrust.

Based on the given above equations, the governing equations of the improved spherical bubble model can be stated by

\[
\frac{d^2 R}{dt^2} = \frac{p_b - p_{env}}{\rho_L R} - \frac{3}{2R} \left( \frac{dR}{dt} \right)^2,
\]

\[
\frac{d^2 r_c}{dt^2} = \frac{n-1}{\rho_r} \left( p_{out} - p_{env} \right) - \frac{n+1}{2r_c} \left( \frac{dr_c}{dt} \right)^2 + \frac{r_c}{R} \frac{d^2 R}{dt^2} - \frac{r_c}{R} \left( \frac{dR}{dt} \right)^2 + \frac{n+3}{2R} \frac{dr_c}{dt} dR,
\]

\[
\frac{dp_b}{dt} = \frac{\gamma m_{in} R g T_0 - \gamma m_{out} R g T_b - \gamma p_b (dV_b/dt)}{V_b},
\]

\[
m_{out} = \left( \frac{r_c}{r_0} \right) m_{in},
\]

\[
m = \int_0^t m_{in} - m_{out} dt,
\]

\[
p_{out} = \frac{r_c}{r_0} \left( p_0 - p_{env} \right) + p_0,
\]

\[
r_0 = \begin{cases} \sin \left( \alpha_0 + \arcsin \left( \frac{r_c}{R} \right) \right) 2 \arcsin \left( \frac{r_c}{R} \right) + \alpha_0 < \pi, \\
\end{cases}
\]

\[
r_0 = \begin{cases} \frac{r_c + R \tan \alpha_0}{2} \arcsin \left( \frac{r_c}{R} \right) + \alpha_0 \geq \pi, \\
\end{cases}
\]

\[
p_{out} = \frac{r_c}{r_0} \left( p_0 - p_{env} \right) + p_0,
\]

\[
T_b = \frac{P_b V_b}{m R g},
\]

\[
\frac{P_s}{\rho_L} - \frac{1}{2} \left( \frac{R^2 \dot{R}}{r_w^2} \right)^2 + \frac{2 \dot{R} R + R^2 \dot{R}}{r_w},
\]

\[
r_w = \sqrt{r^2 + R^2},
\]

\[
F_t = m_{in}v_{in} + A_e(p - p_{env}) + \int_{A_e} (p_s - p_{env})dA,
\]

where \( \gamma \) is the ratio of specific heat, \( R_g \) is the gas constant of air, \( A_i \) is the area of nozzle throat, \( Ma \) is the Mach number at the nozzle exit, \( m \) is the mass of gas in the spherical bubble, \( r_e \) is the radius of nozzle exit, and \( T_b \) is the total temperature of the gas in the spherical bubble. When \( P_b > k_p P_b \), the jet breaks, where \( k_p \) is the model parameter.

The governing equations of the improved spherical bubble model are ordinary differential equations, and these
equations have been solved by using the Runge–Kutta method. The maximum simulation time is 15 s and the pressure range of the simulation is [0.58 MPa, 1.11 MPa]. The initial pressure in chamber is 0.21 MPa. The rising period of pressure is 30 ms and the maximum pressure is 1.11 MPa. The following pressure satisfies equation (12) and falls gradually till $p_0 = 0.58$ MPa.

The process of solving the model is shown in Figure 11. The Runge–Kutta method has been used for solving the model based on the initial and boundary conditions. After getting the results, such as the pressure in bubble, the radius of bubble, the radius of mass outlet channel, and so on, the blockage condition of the jet has been checked. If satisfies, the mass outlet has been blocked at this time and the conditions of mass outlet have been changed. Then, the next time step has been calculated. Repeating this process until the time reach the maximum simulation time $t_{\text{end}}$. At $t = t_{\text{end}}$, the simulation stops.

3.2. Initial and Boundary Conditions. The initial values of the bubble and outlet radius are set $R = 3$ mm and $r_c = 1.1$ mm, and the initial pressures in the chamber and bubble are both 1.5 times of the environmental pressure.

3.3. Model Verification. The model contains four main factors: $n$, $k_m$, $p_c$, and $m_c$. Since the model parameters are affected by the pressure in the chamber, these are calculated in different pressure. The relative error function is established based on the average thrust, the maximum frequency of the thrust, and the maximum median of the thrust move standard deviation, which is shown in

$$\text{relative error} = \sqrt{\left(\frac{\text{mean}(F_{\text{sim}}) - \text{mean}(F_{\text{exp}})}{\text{mean}(F_{\text{exp}})}\right)^2 + \left(\frac{f_{\text{sim}} - f_{\text{exp}}}{f_{\text{exp}}}\right)^2 + \max\left(\frac{\text{median}(\sigma_{\text{sim}}) - \text{median}(\sigma_{\text{exp}})}{\text{median}(\sigma_{\text{exp}})}\right)^2}.$$  

where $F$ is thrust, $f$ is the frequency of thrust, $\sigma$ is the moving standard deviation of thrust, the subscript $\text{sim}$ represents the simulation results, and the subscript $\text{exp}$ represents the experimental results.

The relationship between pressure in the chamber and time satisfies

$$p_0 = Pe^{-0.0588t}.$$  

(12)

The discrepancies between experimental results and those of simulation are displayed in Figure 12. The maximum pressure error between experiment and simulation is 2.19% and the maximum steady-state thrust error is 5.94%.

Through comparing the experimental and simulation results based on the relative error, defined by equation (11), the plotted results in Figure 13 are obtained. When the pressure is less than 1.2 MPa, the relative error is less than 20%.

4. Results and Discussion

4.1. Steady-State Characteristics. Combined with the two-dimensional experiment and Loth’s experiment [3], the basic structure of the underwater jet can be obtained and discussed.

It can be seen from the high-speed photography illustrated in Figure 14 that the jet consists of three major parts: the gas-phase jet core, the gas-liquid mixing region, and the liquid-phase environment area. The gas-liquid mixing region is formed by mixing a high-speed gas jet with the low-speed liquid phase, and the liquid concentration gradually increases from inside to outside.

The underwater jet angle composes of the jet core and the gas-liquid mixing region. Since the transient angle is greatly affected by pulsation and back-attack, the angle of the underwater jet is defined by the time-averaged image of high-speed photography. Figure 15 shows the method of measuring the half angle and the relationship between the half
angle and the pressure in the chamber. The time-averaged angle increases with the increase of pressure, and the increased rate of time-averaged angle decreases with the increase of pressure. The measurement results are shown in Table 1.

4.2. Transient Characteristics. The main transient characteristics of the underwater jet are pulsation and back-attack shown in Figure 16(a). The frequency of underwater back-attack increases first and then decreases with the pressure shown in Figure 16(b). When the pressure in the chamber is greater than 3.5 MPa, the back-attack no longer occurs. The peak frequency of a back-attack is 5.96 Hz at the pressure of 0.8 MPa and pulsation throughout the entire pressure range.

4.2.1. The Back-Attack Phenomenon in the Two-Dimensional Experiment. In the performed two-dimensional experiment, the process of the back-attack phenomenon can be seen more clearly than that of the three dimensional since the entrainment only occurs in the upper and lower directions. Table 2 shows the whole process of a typical back-attack phenomenon when the mean pressure in the chamber is 0.189 MPa. Due to the entrainment effect, the gas-liquid mixing region near the jet axis is narrowed at time $t = 0$ ms. The higher-density mixing medium enters the jet core along the entrainment direction, hindering the jet channel and causing the jet channel to bend upward at $t = 7$ ms. The curved jet hits the high-density medium area, and the velocity decreases rapidly, which causes the gas to gather and form a back-attack phenomenon at 15 ms. The gas caused by the back-attack gathers near the jet core to produce a new gas-liquid mixing region at 19 ms, protecting the jet core area from the influence of the high-density liquid medium. As a result, the flow channel is reestablished at 30 ms.

4.2.2. The Back-Attack Phenomenon in the Three-Dimensional Experiment. Table 3 presents the three-dimensional back-attack process of images captured based on high-speed photography. Figure 17 demonstrates the simulation results of the improved spherical bubble model. When the pressure is lower than 3.5 MPa, due to the entrainment of the jet, the mixing region becomes narrow, the bubble radius reduces, and the liquid phase percentage of the mixing medium grows. The increase of the entrainment mixture density leads to the velocity decrease in the core area of the jet, which blocks the subsequent gas and causes the expansion of bubbles at the nozzle exit. The diameter of the bubble lessens in the oscillatory manner, resulting in jet pulsation. With the development of the jet, the high-density mixing medium is entrained into the core area of the jet. Due to the variation of the density of the entrainment mixing medium along the circumferential direction, the blocking ability is different, yielding the deflection of the jet axis to the lower side of the mixing medium density. Thereby, the channel of the jet would change. The front of the jet directly contacts the low-speed, high-density liquid medium, resulting in the gas gathering, leading to the back-attack. Subsequently, the
radius of the bubble outside the nozzle grows rapidly and enters the next pulsation and back-attack cycle.

Both the two-dimensional and three-dimensional back-attack are the processes in which the jet channel is hindered by the entrainment of the liquid and restored.

The two- and three-dimensional results are significantly different in the shape of the jet. There are two main reasons for the difference between two dimensional and three-dimensional. First, the gas diffusion efficiency of the two-dimensional experiment is lower than that of the three-dimensional experiment because the gas gathered at the exit of the nozzle in the two-dimensional experiment can only dissipate directly from above due to buoyancy. The volume of bubbles outside the nozzle maintains a large size during

Figure 14: Diagrams of the underwater jet structure. (a) Underwater jet structure in two-dimensional experiment. (b) Underwater jet structure in [3].

Figure 15: The half angle of the underwater jet. (a) The method of measuring the half angle. (b) The relationship between the half angle and pressure in the chamber.
the whole jet process and is always connected with the main jet. Secondly, the position of the entrainment medium interfering jet is different. The medium in the two-dimensional experiment can only be entrained from below, while in the three-dimensional experiment, the back-attack caused by entrainment may occur at any position in the circumferential direction.

### 4.2.3. Pulsation Phenomenon

The main difference between pulsation and back-attack is whether the entrainment medium can cause the deflection of the jet axis and break the original jet channel. Figure 18 shows the jet pulsation process under 5.52 MPa pressure. The pulsation phenomenon causes the jet boundary to oscillate near the time-averaged boundary. When pulsation occurs, the density of the entrainment medium is low due to the large bubble radius at the exit of the nozzle. The entrainment medium has insufficient energy to interfere with the core area of the jet, so the jet can maintain the original flow channel.

### 4.3. The Analysis of the Entire Jet Process Simulation

Figure 19 shows the result of the entire jet process simulation using improved spherical bubble model. The pressure in the chamber is the input condition shown in Figure 19(a), which...

<table>
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<th>$P_0/\text{MPa}$</th>
<th>Time-averaged image</th>
<th>Half angle (°)</th>
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<tr>
<td>4</td>
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<td>5</td>
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<tr>
<td>6</td>
<td><img src="image8" alt="Time-averaged image" /></td>
<td>33.02</td>
</tr>
</tbody>
</table>

Figure 16: Transient characteristics of an underwater supersonic jet. (a) Test results of the underwater thrust experiment. (b) Relationship between the back-attack frequency and pressure in the chamber.
satisfies equation (12). It can be seen from Figures 19(b)–19(d) that the back-attack phenomenon continues to happen during the entire jet process, with the radius of the bubble decreasing, the peak of pressure in the bubble, and the peak of thrust reaching.

At the start of the jet process, the pressure in the initial bubble stays stable. The radius of the bubble reaches the maximum, where $R = 2.68$ mm at $t = 32$ ms; then the radius decreases in fluctuation. With the development of jet, the pressure in the bubble fluctuates due to the radius decreasing. When the blockage condition of the jet is satisfied, the jet channel closed and the pressure in the bubble rises rapidly. The back-attack phenomenon happens while the thrust pulsates violently and the volume of bubble spikes. The bubble starts to shrink in fluctuation again after reaching the maximum until the next back-attack occurs. Before the back-attack phenomenon happens, the thrust keeps stable. It means that the bubble is able to protect the core of jet and improves the jet’s stability.

Figure 20 shows the relationship between the normalized back-attack frequency and the pressure in chamber. It can be found that the frequency increases first and then decreases with the increase of pressure and the frequency reaches the maximum at 0.95 MPa. The trend of simulated frequency happens to coincide with the experiment.

### 4.4. Influence Factors of Transient Characteristics.

The improved spherical bubble model contains four parameters, namely, $n, k_m, m_c$, and $k_p$. Figure 21 shows the variation of the model parameters with pressure. $n + 1$ is the dimension of the outlet on the bubble surface, indicating the response of the bubble outlet to internal pressure. It can be seen from Figure 21(a) that the mass loss coefficient, $n$, remains stable and fluctuates around 1.0002 with the increase of pressure in the chamber. Since $(m_{out}/m_{in}) = k_m(r/r_0)^m$, $k_m$ and $m_c$ represent the relative strength of jet entrainment capacity. It can be seen from Figures 21(b) and 21(c) that $k_m$ and $m_c$
Table 3: The back-attack process of the three-dimensional underwater jet.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td><img src="image1" alt="Image" /></td>
<td>Entrain the mixing region</td>
</tr>
<tr>
<td>$t = 1 \text{ ms}$</td>
<td><img src="image2" alt="Image" /></td>
<td>The jet axis deflects downward</td>
</tr>
<tr>
<td>$t = 2 \text{ ms}$</td>
<td><img src="image3" alt="Image" /></td>
<td>The jet has been broken, and the back-attack occurs</td>
</tr>
<tr>
<td>$t = 3 \text{ ms}$</td>
<td><img src="image4" alt="Image" /></td>
<td>Gas gathers at the exit of the nozzle</td>
</tr>
<tr>
<td>$t = 20 \text{ ms}$</td>
<td><img src="image5" alt="Image" /></td>
<td>Recovery of the jet channel</td>
</tr>
</tbody>
</table>

Figure 17: The simulation results at 1 MPa based on the improved spherical bubble model. (a) Thrust-time curve. (b) Bubble radius-time curve.
decrease with the increase of pressure in the chamber, indicating that the relative strength of entrainment decreases with the increase of pressure. $k_p$ indicates the relative anti-interference ability of the jet. When $p_b > k_p p_0$, the jet breaking occurs; it means that the smaller $k_p$, the stronger the relative anti-interference ability of the jet. It can be seen from Figure 21(d) that when the pressure is less than 1 MPa, the relative anti-interference ability of the jet decreases with increasing pressure, and when the pressure is greater than 1 MPa, the anti-interference ability increases.
5. Conclusions

(1) The high-speed photography results and thrust curves of the underwater supersonic jet are obtained by experiments. An improved spherical bubble model is constructed to simulate the low-pressure pulsation characteristics (<1 MPa). The simulation results reveal that the entrainment strength and anti-interference capability are the main factors affecting the transient characteristics of underwater supersonic jets.

(2) The flow field of the underwater supersonic jet is composed of the gas-phase jet core and the gas-liquid mixing region. The farther away from the jet core, the lower the gas concentration. The jet angle increases with increasing pressure, and the growth rate of the angle reduces with the development of pressure.

(3) The transient characteristics of underwater jet are pulsation phenomenon and back-attack phenomenon. The main reason for these phenomena is the interference of the ambient medium to the jet core.
The pulsation of the underwater supersonic jet exists in the entire experimental pressure range. The frequency of back-attack increases first and then decreases with the increase of pressure. For the experimental nozzle with a throat diameter of 4 mm, the peak frequency is 5.95 Hz at 0.8 MPa, and the back-attack no longer occurs when the pressure is greater than 3.5 MPa. The experiments and simulation show that the bubble out of the nozzle is able to protect the core of jet. In each back-attack phenomenon period, the bubble expands rapidly first and shrinks in fluctuation until the back-attack occurs. The entrainment strength of the jet affects the shrinkage rate of the bubble. With the increase of jet stability, the back-attack phenomenon changes to the pulsation phenomenon.

Nomenclature

\[ A_c : \text{Area of the nozzle exit} \]
\[ A_e : \text{Area of the nozzle exit plane excluding } A_c \]
\[ A_t : \text{Area of nozzle throat} \]
\[ C_p : \text{Specific heat capacity at constant pressure} \]
\[ e_p : \text{Unit volume energy of spherical bubble} \]
\[ F_t : \text{Thrust} \]
\[ f : \text{Frequency of thrust} \]
\[ k_m : \text{Parameter of the model} \]
\[ k_p : \text{Parameter of the model} \]
\[ M_a : \text{Mach number at the exit of nozzle} \]
\[ m : \text{Mass of gas in spherical bubble} \]
\[ m_2 : \text{Parameter of the model} \]
\[ m_{in} : \text{Mass flow rate of the gas flowing into the bubble} \]
\[ m_{out} : \text{Mass flow rate of the gas flowing out of the bubble} \]
\[ n : \text{Mass loss coefficient} \]
\[ P : \text{Maximum pressure of compressed air cylinder} \]
\[ p_0 : \text{Total pressure in the chamber} \]
\[ p_0 : \text{Pressure in spherical bubble} \]
\[ p_{env} : \text{Environmental pressure} \]
\[ p_t : \text{Pressure at a distance of } r_w \]
\[ R : \text{Radius of spherical bubble} \]
\[ R_g : \text{Gas constant of air} \]
\[ r : \text{Distance from a point in the liquid to the center of mass outlet channel} \]
\[ r_c : \text{Radius of mass outlet channel} \]
\[ r_e : \text{Radius of nozzle exit} \]
\[ r_w : \text{Distance from a point in the liquid to the center of the spherical bubble} \]
\[ T_0 : \text{Total temperature of gas in the chamber} \]
\[ T_0 : \text{Total temperature of the gas in spherical bubble} \]
\[ T_{out} : \text{Total temperature of gas flow out of the bubble} \]
\[ u : \text{Radial velocity} \]
\[ V_b : \text{Volume of spherical bubble} \]
\[ V_i : \text{Velocity of the gas flowing out of the chamber} \]

Greek

\[ \alpha_0 : \text{Half angle of the jet at } P_0 \]
\[ \rho_0 : \text{Density of gas in spherical bubble} \]
\[ \rho_l : \text{Density of liquid} \]
\[ \gamma : \text{Ratio of specific heat} \]
\[ \sigma : \text{Move standard deviation of thrust} \]

Subscripts

\[ exp : \text{Experimental results} \]
\[ sim : \text{Simulation results} \]

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by equipment pre-study joint fund of China Shipbuilding Industry Co., Ltd. (no. 6141B042802-39). The authors would like to express their gratitude to EditSprings (https://www.editsprings.cn/) for the expert linguistic services provided.

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