Theoretical and experimental study on underwater jet characteristics from a submerged combustion system

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Abstract. In this paper, an exhaust noise underwater is investigated experimentally and theoretically. The effects of high temperature and gas-water two-phase on underwater jet noise are analyzed. Results show that, higher exhaust gas temperatures generate louder jet noise underwater, including radiated noise from the tube orifice and bubble noise after detachment from orifice. But gas temperature has little effect on air-air jet noise. Another conclusion from experimental results is that injecting water into air-air jet system can effectively reduce jet noise but has less effect on air-water jet system. Turbulent dynamic noise, generated by air-air interaction, is the main noise source for air-air jet, but turbulent dynamic noise can be ignored in air-water jet considering gas-liquid density difference. And water droplet injected into air reduces the turbulent kinetic energy of the gas, therefore reduces the turbulent dynamic noise in air-air jet system.

1. Introduction
Submerged combustion systems have been applied for heating liquid by injection of hot combustor exit gases into the surrounding liquid[1-3]. Submerged combustion systems are used to generate propulsive power for autonomous underwater vehicles, such as submarines and torpedoes[4]. In all the submerged combustion applications the exhaust gases are injected into the surrounding liquid [5-8]. Previously published experimental studies [9-13] have described gas-water interaction and suggested that the underwater gas jet is highly turbulent and unsteady, and generate noise. Gas jetting into surrounding liquid has been identified as a main noise source for submerged equipment[14]. The noise makes the autonomous underwater vehicles more detectable. It is therefore important to understand and quantify the sources of noise that might degrade the guidance system.

Many factors are related with the jet noise from a submerged combustion system, such as the nozzle exit cross-sections. Vaibhav K examined exhaust gas signatures under submerged conditions using different nozzle for their effect on sound pressure levels and pressure fluctuations [15], and found that the sound pressure level from the elliptical nozzle is lower than the circular, square and triangular nozzles. In addition, the exhaust gas property also has effects on jet sound pressure level. Yan[16] investigated supersonic steam jet submerged in the quiescent subcooled water experimentally, and found that the shape of steam plume was controlled by the steam exit pressure and water temperature. Zhang[17] compared the noise characteristic of steady and unsteady exhaust gas, and found that the unsteady gas generates higher noise level. He also found that the submerged exhaust noise should consist of noise radiated by exhaust pulsation, noise of bubble formation and breaking. Ma[18] established mathematical model of a steam bubble which breaks in sub cooled water.
The exhaust from autonomous underwater vehicles is unsteady gas-liquid two-phase with high temperature and pressure. Since, the jet noise from a submerged combustion system is complicated. And much work deeds to be done in order to clarify the flow field. In this paper, the effects of temperature and gas-liquid two-phase on jet noise are analyzed experimentally. These studies provide valuable fundamental information for range of applications in energy systems extending from underwater propulsion, evaporator, heater, desalination and waste water treatment.

2. Theoretical study of the underwater exhaust noise

The jet noise from a submerged combustion system under water should be consisting of noise radiated by exhaust pulsation, turbulent noise generated by gas-liquid interaction, bubble noise.

It is straightforward to obtain the Lighthill equation from reference [19] as follows:

$$
\Delta^2 p_s - \frac{1}{c_0^2} p_s = - f + \nabla \cdot F - \frac{\partial^2 \tau_{ij}}{\partial x_i \partial x_j}
$$

Where, $p_s$ is sound pressure, $c_0$ is ambient speed of sound in liquid, $f$ is monopole volume source, $F$ is the force on the volume, and $\tau_{ij}$ is stress tensor.

The first term in the right hand is about mass flow rate and heat flow rate, which is equivalent to a monopole pulse volume source. The second term in the right hand is the divergence of un-steady force imposing on bubble, and it is similar to dipole. The third term represents the fluid turbulence, and it is quadrupole noise source. Monopole noise is proportional to Mach number; dipole and quadrupole noise is proportional to three and five times of Mach number, respectively. Since the Mach number is small underwater, the dipole and quadrupole acoustic can be neglected. Therefore, Eqs.(1) becomes:

$$
\Delta^2 p_s - \frac{1}{c_0^2} p_s = - f
$$

The expression of acoustic radiation underwater is generated by integral Eqs.(2), we therefore have

$$
p_s(r, t) = \frac{\rho_l}{4\pi r} \frac{\partial^2 V_b}{\partial t^2}
$$

2.1. Noise radiated by exhaust pulsation

Based on Eqs. (3), Zhang[17] expressed the radiated noise in terms of exhaust pulsation and heat exchange between gas and liquid.

$$
p(r, t) = \frac{\rho_l}{4\pi r} \left[ \frac{\partial^2}{\partial t^2} q_b + \beta(U_{in} \frac{\partial P_m}{\partial t} + P_m \frac{\partial U_{in}}{\partial t} + \frac{\partial}{\partial t}(P_m U_{in})) \right]
$$

Where $q_b$ refers to the heat transmission between gas and liquid, $U_{in}$ and $P_m$ are the exhaust velocity and exhaust pressure of the gas, respectively.

It is found that heat transmission between gas and liquid, as well as flow unsteadiness (including pressure and velocity fluctuation) generate acoustic emission. The heat transmission $q_b$ increases with the increase of gas-liquid temperature difference, resulting in the increase of radiated noise. In addition, higher gas velocity $U_{in}$, pressure $P_m$ and their change rate generates louder radiated noise.

2.2. Bubble noise

According to Eqs.(2), assuming that shape of the bubble is sphere, take the bubble volume $V_b$ into Eqs.(3) and then we can obtain the expression of noise produced by bubble deformation.

$$
p(r, t) = \rho_0 \left( R^2 \ddot{R} + 2R \dot{R}^2 \right) / r
$$

It shows that bubble diameter and its change rate affect the noise. Higher gas-liquid temperature makes bubble volume change faster, results in a high sound pressure. In addition, the initial bubble
radius size also has effect on the jet noise. When the initial bubble radius size is large, sound pressure level of the noise it caused will be high.

2.3. Turbulent dynamic noise
Turbulent dynamic noise will be produced when high speed gas exhausts into the water, and interacts with surrounding static water. According to Lighthill theory:

\[ W = K \rho_g^2 D V_g^8 / (\rho_0 c_0^5) \]  \hspace{1cm} (6)

Where \( W \) is the total power of jet noise, \( V_g \) is the velocity of gas flow, \( \rho_g \) is the density of the gas, \( \rho_0, c_0 \) is the density of water and sound velocity in water, respectively, and \( D \) is the orifice diameter.

Because density difference for gas and water, turbulent dynamic noise caused by velocity shear in water is much smaller. So temperature mainly has effect on radiated noise from the tube orifice and bubble noise after detach from orifice, whereas has little effects on turbulent dynamic noise.

3. Experimental setup
Figure 1 is a schematic showing of the underwater test system with high temperature exhaust noise. High pressure air supplied by compressor is stored in the gasholder. After warmed up in the air heater, gas will be transported into the underwater exhaust tube, and exhausted into the water, noise produced by this process will be caught by the hydrophone, and then sent to the data acquisition system and software processing system. Gas temperature in the air heater is monitored by temperature control system. The exhaust pipe in water tank is shown in Figure 2. Hydrophone is RHS-30 standard hydrophone. Coordinate of the hydrophone is (0.5m, 0.5m, 0) where take the tube orifice as the origin of coordinate, the pipeline extension direction as x-axis, and the vertical direction as z-axis. Pressure and flow rate of gas in the tube are controlled through pressure sensor and flow meter, respectively. In addition, air liquid mixer is assembled on the tube, and the liquid flow rate is measured by water meter.

4. Experimental results
4.1. Gas-liquid two-phase flow underwater
A complex gas-liquid flow field accompanied with wide-frequency, large acoustic pressure of noise is generated by underwater gas jet. The two-phase flow underwater is related to exhaust velocity. Figure 3 shows the bubble phase flow, and Figure 4 shows the jet phase flow. Two-phase flow field transformed bubble flow phase into jet flow phase along with the gradually increasing of exhaust.
velocity. Wu[20] found, when the flow field transformed bubble flow phase into jet flow phase, the sound pressure at 2 KHz increase nonlinearly.

4.2. Effect of temperature on exhaust noise

Figure 5 shows the effect of temperature on exhaust noise. Gas flow rate is 80 m$^3$/h, water temperature is 13°C. As gas temperature increases from 13°C to 80°C, underwater exhaust noise increase, especial the noise over 3kHz increase approximate 20 dB. In order to verify the reliability of the experiment, another underwater exhaust noise test with flow rate of 140m$^3$/h is carried out, and the results is shown in Figure 6. Underwater exhaust noise with frequency over 6kHz increases approximate 20dB. According to the analysis of theoretical basis, heat transmission between gas and liquid, driven by gas-liquid temperature difference, generate radiated noise from the orifice increases. In addition, with the increase of temperature difference between gas and liquid, it is easier for bubble deformation, which results in the increase of bubble monopole noise. Thus it can be seen that the experimental results are in agreement with the theoretical analysis. It also can be seen that reduce the exhaust temperature is an effective measure to reduce underwater exhaust noise.

This article also compared the air-water jet noise with air-air jet noise. Air-water jet presents air jetting underwater and air-air jet means gas exhausting into air. Figure 7 and 8 show the sound pressure level of the low and high-temperature gas jetting into air. To make sure the reliability of the experiment, two jetting noise tests with flow rates of 80 and 200m$^3$/h are carried out. Figures show that as gas temperature increases from 13 to 80°C, jet noise changes a little. Heat transmission has little effect on turbulent dynamic noise caused by interaction of gases. Compared with effect of temperature on air-water jet noise, it can be seen that temperature mainly has effect on air-water jet noise.
4.3. Effect of water injection on air-water jet noise

With reference to the theoretical analysis, as the density of water is much bigger, turbulent dynamic noise caused by velocity shear in water is much smaller than that in air. And KROTHAPALLI[21] experimentally examined the effect of injection of a small amount of water into the shear layer of jet on the unsteady flow structure and sound generation. The near-flied noise levels were found to be reduced by about 2-6 dB. Thus, to reduce air-air jet noise, we can spray water drop into air-air jet system.

The qualitative description of noise generated by gas-liquid two-phase flow jetting into air and water are made. Figure 9 shows effect of gas-liquid two-phase flow on underwater jet noise. Gas flow rate is 200m$^3$/h, liquid volume ratio of the gas-liquid mixture is 0.8%. Compare underwater jet noise with and without water injection, it can be seen that water injection reduce the underwater jet noise, but the effect is not obvious, only 1dB to 2dB. Figure 10 shows effect of gas-liquid two-phase flow on air-air jet noise. It can be seen that gas with flow rate of 200m$^3$/h mixed with liquid with flow rate of 1.6m$^3$/h can obviously reduce the jet noise frequency, in a maximum 10dB. Air-air jet noise is turbulent dynamic noise caused by interaction between high-velocity gas and surrounding static gas. In conclusion, air-air jet noise can be effectively reduced by water injection.

![Figure 9. Effect of water injection on underwater jet noise.](image)

![Figure 10. Effect of water injection on air-air jet noise.](image)

It can be seen from the above analysis that water injection can reduce the air-air jet turbulent dynamic noise, but only has little effect on air-water jet noise. Those noises have relationship with jet shape. The underwater gas jet flow is surrounded by gas liquid mixture layer, include drop layer and bubble layer. As density difference between gas and liquid is big, turbulent dynamic noise caused by velocity shear is small. High-intensity turbulent dynamic noise from air-air jet is produced at the shear layer between high-velocity gas and static gas around when gas jet from the nozzle and lead a strong shear with gas around. When water drop along with high-speed airjets into ambient air, water drop layer forms with static air around. As density difference between gas and liquid is great, water drop layer reduce turbulent dynamic noise caused by gas velocity shear.

In conclusion, the existence of drop layer is good for reducing the turbulent dynamic noise. As there is already forming the drop layer during air-water jet process, it is not that much helpful by injecting water into the tube. While during the air-air jet process, as the jet speed is higher, velocity shear between jet gas and the static gas is stronger, and the turbulent dynamic noise is bigger, and there is no drop layer, so it has apparent effect for reducing the turbulent dynamic noise through water injection.

5. Conclusions

In this paper, experimental investigation on the effects of high temperature and gas-water two-phase on tube exhaust noise has been hold and the theoretical basis of underwater jet noise has been discussed. These conclusions can be made:

1) Air-water jet noise mainly consists of radiated noise from the tube orifice and bubble noise. Turbulent dynamic noise could be ignored.

2) The heat transmission between high-temperature(80°C) gas and low-temperature(13°C) liquid effects noise of air jet underwater, including radiated noise from the tube orifice and bubble noise. Noise underwater with high frequency increases with the increase of gas-liquid temperature difference.
3) Turbulent dynamic is main source for air-air jet noise, generated by air-air shear. The effect of injection of a small amount of water (0.8% of the volume flow rate of the jet) into the shear layer, on the unsteady flow structure and sound generation are examined. And the near-field noise levels were found to reduce by about 10dB. The reason is that water injection is to forming the drop layer and reducing the turbulent dynamic noise, which is the main part of air-air jet noise.

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