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Research Article

Study on Quantitative Sewage Blowing-Off and Real-Time Sewage Level Detection of Submarine Storage Tank

Kai Yang[1,2] **Yide Liao**[1] **Xubing Chen**[1] **and Xiaodong Yang**[1]

[1]*School of Mechanical and Electrical Engineering, Wuhan Institute of Technology, Wuhan 430205, China*
[2]*School of Physics and Mechanical & Electrical Engineering, Hubei University of Education, Wuhan 430205, China*

Correspondence should be addressed to Yide Liao; 53619772@qq.com

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Aiming at the problems of huge exhaust noise and air bubbles caused by sewage blowing-off at an inappropriate time for a submarine ST, a sewage level detection system is designed, which can detect in real-time the sewage level using a weighing sensor to achieve quantitative sewage blowing-off. Therefore, the theoretical analysis of the sewage blowing-off is carried out, and the process of the sewage blowing-off is simulated by a VOF model of Fluent. From the simulation, the gas-liquid volume distribution diagram, the volume curve of the sewage, and the flow rate curve of the outlet sewage are obtained. Furthermore, the installation and detection method of the weighing sensor are described in detail. Finally, an experimental test system for simulating the sewage blowing-off is established, and an ultrasonic liquid level sensor, capacitance level sensor, and weighing sensor are tested. By comparing the effects of the three sensors, the result shows that the weighing sensor is the most effective for real-time sewage level detection during the process of sewage blowing-off and can effectively reduce the exhaust noise of the sewage blowing-off system.

1. Introduction

The storage tank (ST) is one of the necessary living facilities of a submarine, which is used to store solid-liquid mixed sewage mainly consisting of human excreta and seawater. Due to the limited volume of the ST, about 150 L, the sewage needs to be blown off frequently by high-pressure air. Influenced by the variation of the seawater pressure and the different solid-liquid mixing ratios, the time of sewage blowing-off is unstable. However, the existing sewage blowing-off system cannot detect the sewage level in real-time, which results in a large number of bubbles and a huge exhaust noise when the sewage is completely blown off.

The research on a submarine high-pressure air blowing-off system mainly focuses on the hovering system. By controlling the water level of the hovering ballast tank, the ballast tank mass can be quickly adjusted, and the depth and the pitch angle of a submarine can be controlled [1, 2]. Zhang et al. studied the process used in a high-pressure air blowing-off ballast tank based on a VOF two-phase flow model [3]. Liu et al. designed a small scale model experiment of a high-pressure air blowing-off ballast tank and obtained the drainage performance and key performance parameters [4]. The control approach of a variable ballast system and the fuzzy logic control system can make a ballast tank automatically fill up or empty itself of seawater as desired [5–7]. Liu et al. and Zhao et al. proposed a novel type of water hydraulic variable ballast system to improve control performance and reduce energy consumption when adjusting the ballast water [8, 9]. Xiang et al. summarized the designs and analytical processes of adaptive fuzzy control and fuzzy PID control as well as the trends of the future for fuzzy logic in the field of underwater vehicles [10]. Blowing-off equipment suitable for hovering systems has also been designed by researchers [11]. Xia et al. designed an extra-high-pressure pneumatic blowing valve with a differential pressure control for an emergency blowing-off ballast tank [12]. Yang et al. designed an extra-high-pressure pneumatic blowing valve and established a mathematical model for the valve based on a real gas state equation [13]. Compared with the hovering system, the sewage blowing-off system is smaller in size and its internal medium is more complex, so it is more difficult to detect the liquid level in real time.

In this paper, a sewage blowing-off system using a weighing sensor to detect the sewage level in real time is proposed, which realizes the quantitative sewage blowing-off and effectively reduces the exhaust noise of a sewage blowing-off system.

2. Analysis and Simulation of the Sewage Blowing-Off Model

2.1. Analysis of the Sewage Blowing-Off Model. Valves, flanges, and sensors are widely used in the sewage blowing-off system. In order to simplify the calculation, the physical model is reasonably simplified as a direct connection between the gas cylinder and the ST. The physical model of the sewage blowing-off system is shown in Figure 1.

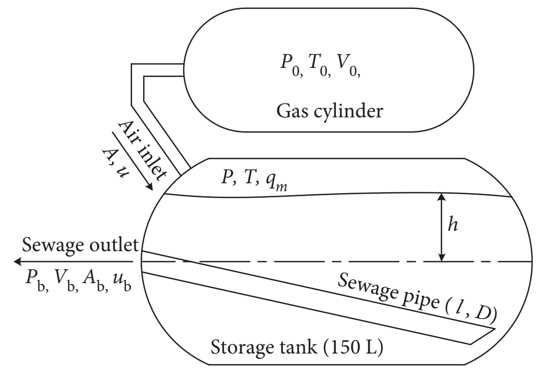

Figure 1: A simplified model of the sewage blowing-off system.

The high-pressure airflow in the sewage blowing-off system is a complex thermodynamic process; the heat transfer between the gas and the pipeline has no effect on the flow of sewage and no mechanical energy is transferred into heat energy. Therefore, in order to simplify the calculation and neglect the influence of secondary factors on the system, the following assumptions are made.

Assumption 1. The ideal gas law can be applied to the whole system gas flow.

Assumption 2. The gas in the gas cylinder is in a stagnant state, the gas flow along the pipeline can be regarded as an isentropic flow, and the gas flow in the ST is in an adiabatic expansion process.

Assumption 3. The sewage in the ST is incompressible and nonviscous, and there is no energy loss when it flows, which conforms to the Bernoulli equation of an ideal liquid.

Assumption 4. The friction coefficient of the sewage pipeline is constant.

We consider that the air flows into the ST from the gas cylinder through a pipeline. Since the cross-sectional area of the gas cylinder is much larger than that of the pipeline, the movement of air in the ST can be neglected. The energy equation can be expressed as

$$c_p T + \frac{u^2}{2} = c_p T_0, \tag{1}$$

with

$$c_p = \frac{\gamma R}{\gamma - 1}, \tag{2}$$

where c_p is the heat capacity at constant pressure, T is the gas temperature in the ST, T_0 is the gas temperature in the gas cylinder, u is the gas velocity at the outlet of the pipeline, γ is the adiabatic exponent, and R is the ideal gas constant.

Based on the isentropic gas flow theory, the gas state equation (3) can be obtained as

$$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\gamma/\gamma-1}, \tag{3}$$

where P_0 is the air pressure in the cylinder and P is the air pressure in the ST.

By equations (1)–(3), the air velocity u and the air mass flow q_m at the outlet of the pipeline can be expressed by equations (4) and (5).

$$u = \sqrt{2c_p T_0 \left[1 - \left(\frac{p}{p_0}\right)^{\gamma-1/\gamma}\right]}. \tag{4}$$

Then,

$$q_m = \rho u A = \rho_0 A \left(\frac{p}{p_0}\right)^{1/\gamma} \sqrt{2c_p T_0 \left[1 - \left(\frac{p}{p_0}\right)^{\gamma-1/\gamma}\right]}, \tag{5}$$

where A is the area of the pipeline.

Taking the outlet center section of the ST as the datum, the Bernoulli equation of the sewage level and the outlet section can be expressed as

$$h + \frac{P}{\rho g} + \frac{u_1^2}{2g} = \frac{P_b}{\rho g} + \frac{u_c^2}{2g}, \tag{6}$$

where h is the height of the sewage level, P_b is the seawater pressure, ρ is the density of the sewage, u_1 is the velocity of the sewage surface, and u_c is the velocity of the outlet sewage.

We consider that the cross-sectional area of the ST is much larger than that of the sewage outlet. Therefore, the velocity u_1 of the sewage surface can be ignored. The velocity u_c of the outlet sewage can be obtained as

$$u_c = \sqrt{2gh + 2\frac{P - P_b}{\rho}}. \tag{7}$$

The volume variation ΔV of the sewage blown off in time Δt can be expressed as

$$\Delta V = \mu A_c u_c \Delta t = \mu A_c \Delta t \sqrt{2gh + 2\frac{P - P_b}{\rho}}. \tag{8}$$

Then,

$$\frac{dV}{dt} = \mu A_c \sqrt{2gh + 2\frac{P - P_b}{\rho}}. \tag{9}$$

The height variation Δh of the sewage level in time Δt can be expressed as

$$\Delta h = \frac{\Delta V}{F(h)}, \tag{10}$$

where $F(h)$ is the area function of the cross section of the ST.

Here,

$$\frac{dh}{dt} = \frac{dV}{dt} \cdot \frac{1}{F(h)}. \tag{11}$$

Then,

$$\frac{dh}{dt} = \frac{\mu A_c}{F(h)} \sqrt{2gh + 2\frac{P - P_b}{\rho}}. \tag{12}$$

Equations (9) and (12) reflect the instantaneous variation of the sewage volume and the sewage level height, respectively. Compared with the seawater pressure P_b and the air pressure p, the sewage level height h is small and can be ignored. Therefore, the volume of the sewage blowing-off V and the height of the sewage level h are both inversely proportional to the seawater pressure P_b and directly proportional to the air pressure p.

2.2. Simulation of the Sewage Blowing-Off Model Based on Fluent. By using computational fluid dynamics, we can predict the performance and provide solid guidelines during the design phase of modelling and parameter estimation. Therefore, the process of sewage blowing-off and the gas-liquid volume distribution can be clearly observed by using the volume of fluid (VOF) model of Fluent. And a simulation model of the ST with a volume of 150 L is set up, and its 3D model is divided into 113925 hexahedral meshes by using the multizone sweep meshing.

In order to simulate the actual condition, the boundary conditions are set as pressure inlet and pressure outlet; the inlet air pressure is 3.4 MPa, and the outlet seawater pressure is 1.8 MPa. The fluid medium in the ST is set to gas-liquid two-phase, where one phase is seawater and the other phase is air. Before the simulation, a gravity acceleration of $9.8\,\mathrm{m/s^2}$ is added in the vertical direction, and the air volume fraction of the whole fluid area in the ST is 0, so the initial state of the ST is filled with seawater. The gas-liquid volume distribution diagram of the 3D model and the middle section of the ST during the blowing-off time from 5 s to 40 s are shown in Figure 2.

Figures 2(a)–2(h) show the gas-liquid volume distribution of the 3D model and the middle section of the ST at different blowing-off times. The blue area and the red area represent seawater and air, respectively, and the other coloured areas represent different air proportions of the gas-liquid mixtures. The volume fraction of air is shown at the bottom of each picture at every time.

By monitoring the simulation process, the volume curve of the sewage in the ST and the flow rate of the outlet sewage at different seawater pressures are obtained as shown in Figures 3 and 4.

As can be seen from Figures 2–4, when the sewage blowing-off begins, the air enters into the ST and forms a mixing layer at the gas-liquid interface. At this moment, the flow rate of the outlet sewage increases rapidly and maintains basic stability at a certain flow rate. With the continuous sewage blowing-off, three distinct layers are formed in the ST. The upper layer is air and the middle layer is gas-liquid mixing, and both of the two layers spread continuously with the entry of air. The lower layer is water. Due to the large flow rate of the outlet sewage, the volume of the sewage in the ST reduces rapidly, and the flow rate of the outlet sewage decreases sharply. Since then, the sewage is basically emptied, and a small amount of residual sewage diffuses throughout the ST. The lower the pressure of seawater, the greater the pressure difference between high-pressure air and seawater. And the larger the pressure difference, the faster the flow rate of the outlet sewage and the faster the volume change of the sewage in the ST.

3. Method Study on the Real-Time Sewage Level Detection

In order to realize the quantitative sewage blowing-off and reduce the exhaust noise, it is effective to detect the sewage level in real-time during the blowing-off process. Sensing technology is widely used in underwater vehicles [14], but the corrosive nature of seawater, biofouling, pressure resistant enclosure, data transfer reliability, and the dynamic nature of the ocean itself create great limitations in an underwater environment [15].

For the sewage blowing-off system, the ST is a sealed container withstanding high pressure, and the sewage is a solid-liquid mixture of human excreta and seawater in different proportions. The sewage level will oscillate violently when the sewage is blown off by the high-pressure air. Therefore, it is difficult to accurately detect the sewage level in real-time by using conventional sensors in the process of sewage blowing-off.

To solve this problem, a sewage blowing-off system using a weighing sensor to detect the sewage level in real-time is proposed. The ST is installed horizontally and is simply supported by a beam structure. The sewage outlet is hinged with the base through the flange, and the bottom of the other end is equipped with a weighing sensor. Therefore, the weighing sensor can detect about one-half of the sewage weight in real-time, and the real-time sewage level and the total sewage

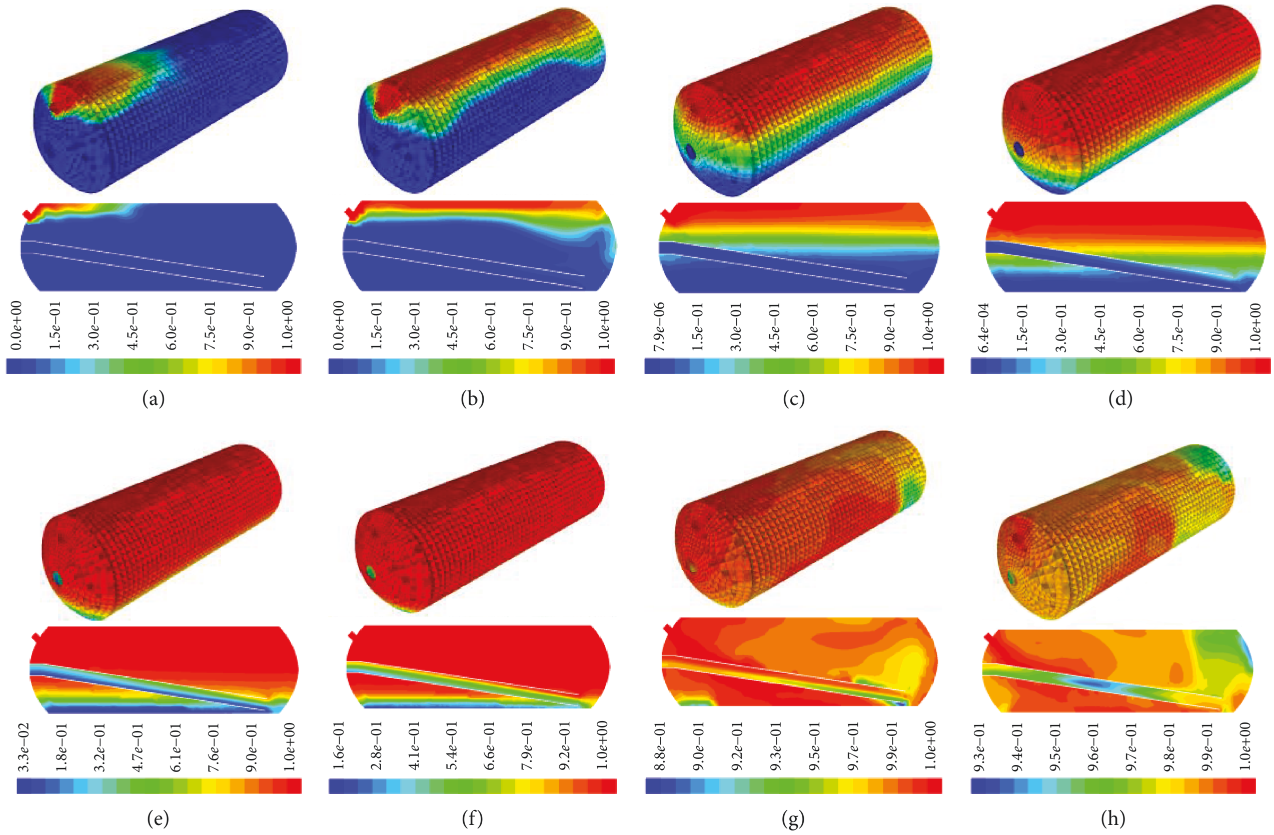

Figure 2: Gas-liquid volume distribution during the blowing-off time from 5 s to 40 s: (a) 5 s, (b) 10 s, (c) 15 s, (d) 20 s, (e) 25 s, (f) 30 s, (g) 35 s, and (h) 40 s.

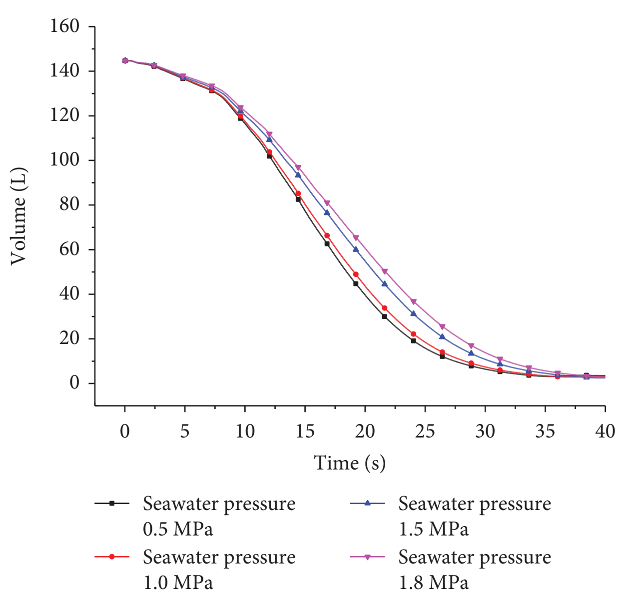

Figure 3: Volume curve of the sewage in the ST.

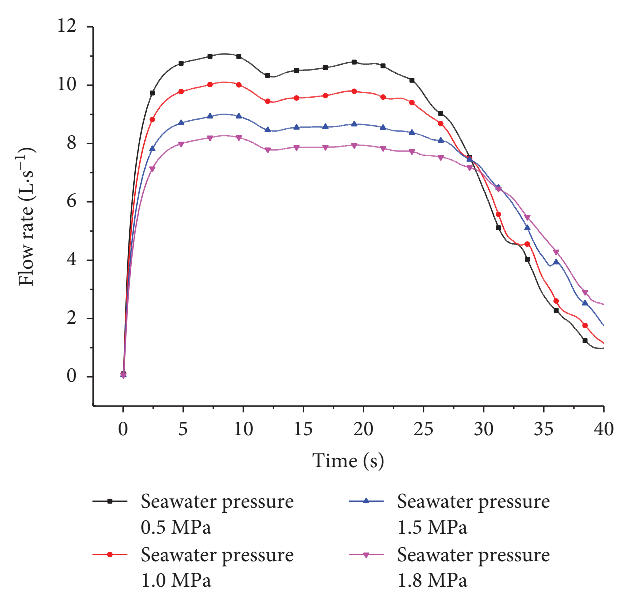

Figure 4: Flow rate curve of the outlet sewage.

displacement can be obtained by conversion. In addition, the sewage inlet is connected to the bedpan by a flexible hose, which makes the ST rotate flexibly and enables it to avoid the influence of the bedpan or pipeline based on the accuracy of the sewage weight detection.

When the system operates, the sewage is blown off by the high-pressure air and the weight of the ST decreases continuously. When the weighing sensor detects the lower limit of the ST weight, it feeds back a signal to the system. Then, the system closes the sewage outlet valve and the high-

Figure 5: Experiment testing system.

Table 1: Detection effect of the three sensors.

	Sensor	Precision	Response state	Response time
1	Ultrasonic liquid level sensor	±0.5%	Effective	Delay of about 60 s to 80 s
2	Capacitance level sensor	±0.5%	Ineffective	—
3	Weighing sensor	±0.1%	Effective	Sensitivity

pressure air valve, which realizes the sewage level detection and the quantitative sewage blowing-off.

4. Experimental Testing and Results Discussion

4.1. Experimental Testing. In order to verify the effect of real-time sewage level detection, an experimental test system for simulating the sewage blowing-off is established as shown in Figure 5.

In addition to the weighing sensor, an ultrasonic liquid level sensor and a capacitance level sensor are tested and compared. The ultrasonic liquid level sensor is adsorbed on the outer wall surface of the ST through its two magnetic probes, and the capacitance opens a hole on the wall surface of the ST and is inserted inside it.

The sewage is replaced by salt water and soil. The soil accounts for about 10% of the total weight of the sewage, and the salinity of the salt water is about 3.5%. The sewage is discharged into the ST from the bedpan, and the ST is connected with a back-pressure simulated container through a metal hose. By controlling the pressure of the back-pressure simulated tank, the seawater pressure can be simulated and adjusted. The overflow valve is used to maintain the pressure of the seawater during the process of the sewage blowing-off, and the pressure relief valve is used to regulate the pressure difference between the air and the simulated seawater.

4.2. Results and Discussion. The detection effects of the three sensors are shown in Table 1.

The ultrasonic liquid level sensor detects the liquid level by transmitting velocity differences in different media through ultrasonic waves, and its characteristics are suitable

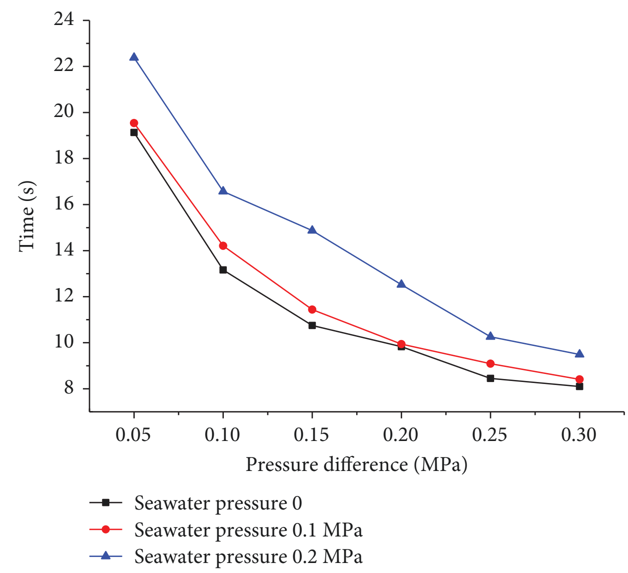

Figure 6: Time of the sewage blowing-off at low simulated seawater pressure.

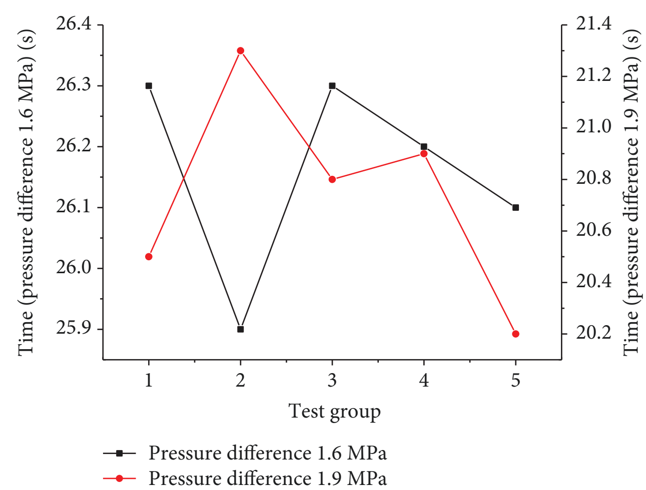

Figure 7: Time of the sewage blowing-off at a simulated seawater pressure of 1.8 MPa.

for the noncontact liquid level detection of a pressure vessel. But for the ST, either the gas-liquid oscillation intensity or the dirt thickness of the inner wall surface has great influence on its detection effect. These factors lead to its response delay of about 60 s to 80 s. The capacitive liquid level sensor uses the weak change of the different dielectric capacitance near the electrode to realize a liquid level signal output. However, when the solid-liquid phase containing salt is attached to its electrode, it will cause greater interference to the response. The weighing sensor detects the sewage level by detecting the weight of the sewage in the ST; it responds well in the whole experimental testing process and its signal output is stable and repeatable.

In order to improve the accuracy of the experimental testing, the time of quantitative blowing-off 100 L of the sewage is tested by using the weighing sensor. Limited by the test

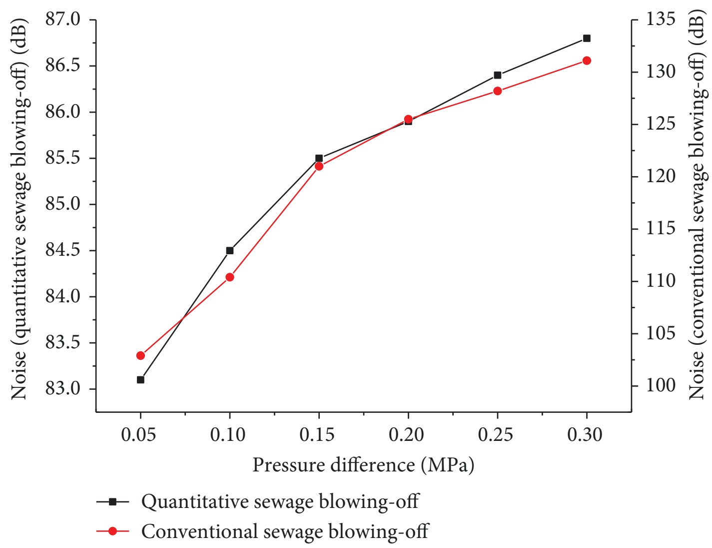

Figure 8: The exhaust noise levels of conventional sewage blowing-off and quantitative sewage blowing-off.

conditions, the simulated seawater pressure is set at low pressure (0, 0.1 MPa, and 0.2 MPa) and high pressure (1.8 MPa), and the pressure difference between the high-pressure air and seawater is adjusted by controlling the pressure of the high-pressure air. The time of the sewage blowing-off under different pressure differences is tested as shown in Figures 6 and 7.

As can be seen from Figure 6, the lower simulated seawater pressure (0, 0.1 MPa, and 0.2 MPa) has little effect on the time of the sewage blowing-off. But a smaller pressure difference, such as 0.05 MPa, can quickly blow the sewage off. And when the pressure difference increased from 0.05 MPa to 0.3 MPa, the blowing-off time obviously decreased.

In Figure 7, the time of the sewage blowing-off at a pressure difference of 1.9 MPa is about 5 s or 6 s faster than that of the pressure difference of 1.6 MPa. The data indicate that the time of the sewage blowing-off is proportional to the pressure difference, which is basically consistent with the result of the above model and the simulation analysis.

The exhaust noise levels of the conventional sewage blowing-off and quantitative sewage blowing-off are both tested by the noise meter as shown in Figure 8. The experimental environment noise is about 60 db, and the simulated seawater pressure is 0.2 MPa.

As can be seen from Figure 8, with the increase of the pressure difference, both the exhaust noise levels of conventional sewage blowing-off and quantitative sewage blowing-off are enhanced. The exhaust noise of quantitative sewage blowing-off is within the range of 90 dB, and the maximum exhaust noise of conventional sewage blowing-off is more than 130 dB. Therefore, quantitative sewage blowing-off can effectively reduce the noise of the sewage blowing-off system.

5. Conclusion

In this paper, the real-time liquid level detection is applied to the sewage blowing-off system, which effectively realizes the quantitative sewage blowing-off. The main conclusions are drawn as follows:

(1) By using the weighing sensor, the sewage level can be detected in real-time and the quantitative sewage blowing-off can be achieved, which can effectively avoid the inappropriate blowing-off time

(2) The time of the sewage blowing-off is mainly related to the pressure difference between the high-pressure air and seawater. A higher pressure difference can lead to a shorter blowing-off time

(3) Both the exhaust noise levels of conventional sewage blowing-off and quantitative sewage blowing-off are enhanced with the increase of pressure difference, and the quantitative sewage blowing-off can effectively reduce the noise of the sewage blowing-off system

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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