Characteristics of Air-Water Flow in An Emptying Tank Under Different Conditions

Jialing Liang\textsuperscript{a}, Yiyi Ma\textsuperscript{b}, Yi Zheng\textsuperscript{c}

\textsuperscript{a} Master Student, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China. E-mail: 2201207@zju.edu.cn
\textsuperscript{b} Assistant Professor, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China. E-mail: yiyima@zju.edu.cn (Corresponding author)
\textsuperscript{c} Engineer, Zhejiang Communications Construction Group Co., Ltd, Hangzhou, 310053, China. E-mail: 470160232@qq.com

\begin{abstract}
This paper experimentally studied the features of air-water flow during the emptying of a water-filled prismatic tank with a bottom orifice under different conditions. The experiments were conducted with both circular and elliptical orifices, with and without ventilation. The evolution of bubbles, water pressure variation, and water level change with time were recorded in the experiments and analyzed. Based on the results, the evolution of bubbles could be mainly divided into three stages: formation, deformation, and decomposition. Ventilation was found important to the emptying process, with which the drainage efficiency was much higher than that under the unventilated condition. Additionally, under the unventilated condition, the drainage efficiency with the circular orifice was slightly higher than that with the elliptical orifice.
\end{abstract}

Keywords: Air-water flow, Bubble, Emptying process, Drainage efficiency, Orifice.

When emptying liquid-filled bottles, periodical generation of bubbles at the bottle opening can be observed, accompanied by a “glug-glug” sound, which is one of the most common two-phase flow phenomena in daily life. Similar phenomena can be found in many industrial applications, such as bottle rinsing [1] and filling [2]. It has been received much attention due to its effect on the liquid discharge rate, which is vital to these industrial processes. For example, it is one of the dominant factors for bottle washing/rinsing efficiency [1].

Extensive studies have been conducted on the drainage efficiency of emptying bottles, tanks, pipes, or other containers [3–5]. The air-flow patterns during the emptying process can be commonly divided into three types [6], including no flow, oscillatory flow and counter flow. The parameters affecting the air-water flow features during the emptying process mainly include the volume, exit size, inclination of the container, and the initial liquid filling ratio, etc. [3–6]. Tang and Kubie [7] studied the emptying processes with the bottle exit orienting in various directions. Whalley [8], Geiger et al. [9] and Rohilla and Das [10] reported that there was a critical bottle inclination angle \( \theta_{crit} \). When the bottle inclination angle \( \theta < \theta_{crit} \) the emptying time decreased with the increase of \( \theta \) while it turned asymptotic when \( \theta > \theta_{crit} \). Note that the effects of the inclination degree of containers on the emptying time varied with the exit size [9]. Mayer [11] and Kordesran and Kubie [12] reported that the emptying time reduced with the increase of the exit diameter. Additionally, Whalley [8] found that a higher water temperature resulted in a shorter emptying duration. Nevertheless, the height of the container and the initial liquid depth inside it had a limited effect on the drainage efficiency of the emptying process [4,13]. Kumar et al. [3] controlled the ventilation conditions during the emptying and found that the discharge rate increased with the opening rate of the top air vent.

The drainage efficiency during the emptying processes has been defined quantitatively. Wallis [14] introduced flooding constant, defined as \( C = 0.598(\rho_\text{g} \frac{1}{\rho_\text{l}} + 1) \) to describe the relationship of gas-phase velocity and liquid-phase velocity when emptying, with \( \rho_\text{g} \) and \( \rho_\text{l} \) being the densities of gas and liquid, respectively. A larger \( C \) indicated a shorter duration for the emptying process.
\( \sqrt{U_g} \) based on Wallis’s work, where \( U_g \) and \( U_l \) represent the superficial velocities of gas and liquid, respectively.

Although there have been extensive studies on emptying processes of various containers, most of them were conducted with a circular exit and those under the conditions of non-circular exits are limited. Non-circular orifices are also used in some chemical engineering, like the elliptical orifice at the bottom of the hanging down camber [15]. Additionally, the majority were under unventilated conditions, while few have explored the effects of ventilation on air-water flow features. This paper experimentally studied the air-water flow during the emptying process of a water-filled prismatic tank with a bottom orifice, focusing on the characteristics of air bubbles generated at the orifice and their effects on the drainage efficiency. The experiments were conducted with both circular and elliptical orifices under top-sealed and top-ventilated conditions. The impacts of exit shapes and ventilation conditions on the emptying process were discussed. The findings of the current study can provide information for optimizing relevant industrial processes, e.g., orifice design optimization, ventilation condition control, or any other aspects.

The schematic of the experimental setup is shown in Fig. 1a, which mainly consisted of a Plexiglas prismatic tank of 200 mm × 200 mm × 500 mm, a water pump, and a parameter measurement system (including water/air pressure transducers and a data acquisition system). The experimental setup was a self-circulating system by using a submersible pump. An orifice was opened in the center of the tank bottom for water drainage. Two types of bottom orifices, i.e., circular and elliptical orifices, were tested in the experiments, as shown in Fig. 1b. The diameter of the circular orifice was 25 mm, and the dimensions of the elliptical orifice were 50.4 mm × 12.4 mm. Note that the two types of orifices had the same area of 490 mm² and the effect of surface tension is considered insignificant in the current study. At the top of the tank, there was a slit of 2 mm × 20 mm (see Fig. 1a).

The ventilation condition of the experiments was controlled by opening or closing the slit.

In the experiments, the water pressure at the tank bottom was monitored by a water pressure transducer placed adjacent to the bottom orifice with a measuring range of 0-5k Pa (HQ100, manufactured by Baoji Huaiqiang Inc.). The real-time water pressure data were recorded by the data acquisition system (INV360U Data Acquisition System, manufactured by China Orien Institute of Noise & Vibration) connected with a computer. The appearance of the air bubbles and the variation of the tank’s water level were both recorded with a high-frequency camera (Osmo Action, manufactured by DJI Inc.). The resolution of the camera was set to be 1980 × 1080 pixels, and the frequency was 240 frames/s. Backlighting with a LED panel was utilized for the illumination in the experiments.

Before the experiments, the bottom orifice was sealed with waterproof tape, and water was pumped into the tank till a certain water level of \( H = 250 \) mm. To begin the experiment, the waterproof tape was torn carefully, and water flowed out of the tank through the bottom orifice. The experiments of tank emptying were conducted under four conditions, with different types of bottom orifices and ventilation conditions, as listed in Table 1. The experiments were conducted at a room temperature of about 10 °C.

Essentially, the emptying process of the water-filled tank is the mass exchange of the internal water and the ambient air, during which air penetrates into the tank periodically in the form of bubbles through the bottom orifice. The bubbles captured by the camera in the experiments are shown in Figs. 2 and 3. From the figures, the evaluation of bubbles in water can be mainly divided into three stages, including formation, deformation, and decomposition. Note that bubbles only occurred under the top-sealed condition, and none was observed under the top-ventilated condition.

![Schematic of (a) experimental setup and (b) bottom orifices.](image)

**Fig. 1.** Schematic of (a) experimental setup and (b) bottom orifices. (1) Opening for water supply, (2) slit for ventilation, (3) tank, (4) bottom orifice, (5) water pressure transducer, (6) data acquisition system, (7) computer, (8) camera, (9) submersible pump

<table>
<thead>
<tr>
<th>Cases</th>
<th>Bottom Orifice</th>
<th>Shape</th>
<th>Dimensions (mm)</th>
<th>Area A (mm²)</th>
<th>Ventilation conditions</th>
<th>Initial water level ( H ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>circular</td>
<td></td>
<td>( D = 25 )</td>
<td>490</td>
<td>top-sealed</td>
<td>250</td>
</tr>
<tr>
<td>II</td>
<td>circular</td>
<td></td>
<td>( D = 25 )</td>
<td>490</td>
<td>top-ventilated</td>
<td>250</td>
</tr>
<tr>
<td>III</td>
<td>elliptical</td>
<td>( X \times Y = 12.4 \times 50.4 )</td>
<td>490</td>
<td>top-sealed</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>elliptical</td>
<td>( X \times Y = 12.4 \times 50.4 )</td>
<td>490</td>
<td>top-ventilated</td>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>

*D = circular orifice diameter; \( X, Y \) = short/long axes of the elliptical orifice.*
The evaluation of the first bubble generated at the tank bottom orifice in Case I, where the orifice was circular, and the top of the tank was sealed, is shown in Fig. 2. In the stage of bubble formation, as shown in Fig. 2a to 2c, the water level in the tank drops immediately as the exit is open, which results in the sudden drop of air pressure in the upper space of the tank. Driven by such pressure difference inside and outside the tank, an air passage is formed (see Fig. 2b), which allows the ambient air to enter the tank and forms a bubble at the orifice. The bubble grows gradually until the pinch-off (see Fig. 2c), which means the end of the formation stage. Subsequently, the air bubble, exhibiting a spherical shape, rises slowly in water and keeps deforming during this process, as shown in Fig. 2d to 2f. The bubble gets flattened gradually and its central part collapses first, which is the start of the decomposition stage, as shown in Fig. 2g. As the bubble moves upwards further, its edge gets crushed and gradually breaks up into a group of small bubbles (see Fig. 2h to 2j). Finally, the small bubbles reach the water surface and are released into the upper space of the tank.

When the bottom orifice is elliptical, the bubble characteristics are different from those generated at the circular one. Figure 3 shows the evaluation of the first observed bubbles under Case III, with an elliptical orifice of 12.4 mm × 50.4 mm. The entire evaluation of the bubble can also be divided into three stages of formation, deformation, and decomposition, while each performs differently. In the formation stage, a big bubble and a small bubble are generated at the bottom orifice, but they get consolidated shortly, as shown in Fig. 3a and 3b. In the deformation stage, one of the most significant features of the bubble is that its geometry changes from "spherical" to "smoke ring", as shown in Fig. 3d. The "smoke ring" expands radially as it rises further, and at a certain location, its edge starts to be crushed (see Fig. 3e to 3h). Compared with the bubble generated from the circular orifice, the ones formed at the elliptical orifice exhibit a wider variety of shapes.

The pressure variation at the tank bottom in the first three seconds of emptying is shown in Fig. 4a, and that during the entire emptying process is shown in Fig. 4b. From Fig. 4a, the pressure variation shows periodical features in Cases I and III. Once the emptying process starts, the pressure at the tank bottom drops rapidly from \( P = 2450 \text{ Pa} \), i.e., the hydrostatic pressure for the initial water depth of \( H = 250 \text{ mm} \), to close to zero, within about 0.5 seconds. The pressure then rises to about 500 Pa and varies periodically later. Additionally, the pressures measured at the bottom of the tank in Cases II and IV, with the ventilation by the slit on the top, are lower than the static pressure caused by the water depth. It indicates that negative air pressure occurs in the airspace of the tank, which is due to the limitation of air supply from the slit. The value of the negative air pressure is the difference between the pressure measured at the tank bottom and the static pressure, which is about -600 Pa in both cases.

The mechanism for air bubble generation at the bottom orifice was studied based on the camera images and the pressure data. Once the pressure reaches the lowest, a bubble begins to be formed at the bottom orifice. As the pressure increases, the bubble grows and it completes the formation stage when the pressure reaches about 500 Pa. Afterwards, the bubble detaches from the bottom orifice and correspondingly, the pressure decreases. The water level in the tank keeps dropping and then the second bubble starts to be formed. Such processes are repeated until the end of the emptying process. Under the top-ventilated condition, the pressure variation becomes insignificant, as shown in Fig. 4. Based on the pressure variation, the frequency of bubble formation at the bottom orifice is about 2.5 Hz. According to the mathematical model proposed by Clanet and
Searby [13], during the emptying processes, the period of bubble formation depends on the physical properties of air and water, the water depth in the tank and the orifice geometry.

The variations of water level with time during the tank emptying process in Cases I-IV are presented in Fig. 5, where the solid black line is for the theoretical discharge curve. The equation for the theoretical discharge curve is derived in the following. The bottom orifice flow discharge rate is

\[ Q = \mu A \sqrt{2gh}. \tag{1} \]

Here, \( \mu \) = discharge coefficient, \( A \) = area of bottom orifice, and \( h \) = water depth in the tank. Based on mass conservation, the volume of water flowing out from the orifice during dt equals the reduced volume of water in the tank, i.e.,

\[ Qdt = \mu A \sqrt{2ghdt} = A_0dh, \tag{2} \]

where \( A_0 \) is the cross-sectional area of the tank. By integrating Eq. (2) and re-arranging the equation, the theoretical discharge curve is obtained:

\[ h = \frac{1}{2} \left(1 - \frac{1}{2} \frac{\sqrt{2g\mu A}}{A_0} \right)^2. \tag{3} \]

The drainage efficiencies of the tank in Cases I-IV can be read from Fig. 5. From the results, the tank drainage efficiency under the top-sealed conditions is much lower than those under the top-ventilated conditions, which indicates the significant effect of ventilation on the drainage efficiency. Also, the \( h-t \) curves under the top-ventilated conditions are still slightly lower than the theoretical curve, indicating the limitation of air supply by the slit on the top of the tank in the current experiments.

In addition, the \( h-t \) curves under the top-ventilated conditions are concave, consistent with the theoretical curve, which means that the discharge rate is larger at the early stage of the emptying process while gets smaller with time. Under the top-sealed conditions, the \( h-t \) curves are convex slightly, indicating an increase in the discharge rate with time. Under the top-ventilated conditions, the flow discharge rate is dominated by gravity, while under the top-sealed conditions; the flow discharge rate is affected by the gravity, the pressure difference inside and outside the tank, as well as the bubbles. The different dominant factors lead to the two types of \( h-t \) curves under different ventilation conditions.

Based on Fig. 5, under the top-sealed conditions, the emptying time of the filled tank in Case III with the elliptical orifice is slightly larger than that in Case I with the circular orifice. Cao et al. [16] reported that for orifice flow, under the condition of the same area, a longer wetting perimeter of the orifice can result in larger frictional resistance to outflow. In the current experiments, the circular and elliptical orifices have the same area, while their wetting perimeters are 78 mm and 108 mm, respectively, which indicates a smaller frictional resistance from the circular orifice to the outflow. It is the reason for the slightly higher drainage efficiency of the circular orifice.

The emptying processes of a water-filled tank with both circular and elliptical bottom orifices were studied experimentally in this paper. The effects of orifice shape and ventilation conditions on the air-water flow features during the emptying process were investigated. The bubble features were analyzed based on the water pressure measurement and the synchronous video recording. Three stages of bubble development were divided, including the formation stage, the deformation stage, and the decomposition stage. During the emptying processes, the water pressure at the tank bottom presented periodical features and varied between 400 Pa and close to zero in the experiments. The water pressure variation corresponded to the generation frequency of bubbles at the orifice, which was about 2.5 Hz in the current study. The drainage efficiencies of the tank varied with
the ventilation conditions. To achieve efficient water drainage in industries, the ventilation condition should be considered carefully for sufficient air supply. Additionally, under the top-sealed conditions, the drainage efficiency of the tank with the circular orifice was slightly higher than that with the elliptical one, which was due to the less frictional resistance of the circular orifice to the outflow.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The writers gratefully acknowledge financial support from the Fundamental Research Funds for the Central Universities (2020QNA4017).

References