Establishment and application of continuous real–time release model for storage tank

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Abstract: The calculation of the release of liquid hazardous chemicals storage tanks is an important part of the quantitative risk assessment of accidents. This paper mainly establishes a continuous real–time release model based on the instantaneous mass flow $Q_m$ model. Meanwhile, the software function module was analyzed, and programming software was developed using C# language for model solving. A series of experiments for repeated leakage tests was designed and the discharges through three small holes with different heights for 200 s were observed. The results show that the continuous real–time leakage model is effective, and the deviation between theoretical and experimental release amounts are within a reasonable range. The higher the liquid level above the leak hole is, and the smaller the height of the leak hole from the ground is, the greater the flow rate at the leak orifice is and the smaller discharge rate change is. Therefore, the deviation between the theoretical release amount $M_t$ and the experimental average release amount $M_a$ is greater while the height of the leak hole from the ground is smaller, which indicates that the smaller the distance from the leak orifice to the ground, the greater the influence of the empirical discharge coefficient $C_0$ on the release amount $M$.

Key words: storage tank; continuous real–time; release model; leakage test; hole discharge

1. Introduction

The storage tanks are used to store high-energy material like liquid chemical. Release from a liquid hazardous chemical storage tank occurred if the steel storage tank was improperly maintained, gradually corroded or suddenly cracked [1]. Incidents including fire and explosion or poisoning and suffocation caused major casualties and property losses when the released liquid evaporated and reached a certain concentration [2–4]. Committee for Prevention of Disaster published some guidelines to identify, analyze, calculate and evaluate incidental releases of hazardous materials of pipelines, tanks and pressure containers, by using quantitative risk assessment and qualitative risk assessment [5–7]. In previous research, scholars have studied the quantitative and qualitative risks about tank accidents. For instance, CFD software was used to simulate and analyze the catastrophic dyke overflow accident of oil tanks, and obtain the impacting factors including tank volume, the height of the fire dam, the nature of
the oil, the arrangement of the tank group, and rupture patterns [8]. Luo et al. carried out comprehensive
study for the failure probability of tank leakage level by fishbone diagram and risk matrix analysis
method, which can mitigate the risk of accidents [9]. A model was used to study the dynamic process of
oil leakage in a double–hull oil tanker [10]. Probabilistic method was used to analyze hazardous
chemical spills, establish a quantitative risk assessment model, determine acceptable risk levels, and
evaluate tanks in an industrial park [11]. The accidental release of long–distance pressurized oil pipelines
was analyzed, the model to calculate accumulated volume was obtained, and finally its practicality and
accuracy was testified by experiments [12]. These researches of predecessors provide the references to
resolve the continuous real–time release model for storage tank in this paper.

At present, the quantitative risk assessment of tank leakage accidents is characterized by the
multiplication of the possible consequences of the accident and the frequency of accidents [5–7, 13]. The
possible consequences of the accident are the basis for studying the risk of the accident, and the
consequence calculation of the quantitative risk accident was closely related to the release of toxic and
hazardous substances in the accident [12, 14–15]. The leakage analysis for vertical tank was estimated
by instantaneous mass flow rate or Bernoulli equation [16–17]. However, the accuracy of the liquid level
gauge used in industrial tanks is shown at millimeter level. When the valve of inlet/outlet is closed, the
liquid storage tank is in a relatively static state [18]. Once the manual safety inspection in the tank area is
not fulfilled timely or the flammable and explosive toxic gas detector fails, the leakage amount from the
tank liquid dropping level is difficult to be assessed [19], especially for a large–capacity storage tank
(such as an internal floating tank, volume $V = 50000 \text{ m}^3$, diameter $D = 60 \text{ m}$, tank height $H = 19.44 \text{ m}$;
when the liquid level drops by 1 mm, the leaked liquid is about $2.827 \text{ m}^3$).

This study mainly focuses on the relationship between continuous real–time release amount $M$ and
leakage time $t$ of liquid hazardous chemicals vertical tank, and the model of $M$ to solve the practical
engineering problem of tank leakage calculation is obtained, which provides an effective solution for
enterprise safety management and accident prevention.

2. Mathematical Modeling

2.1. Instantaneous Mass Flow Model

In the existing standard "Guidelines for Quantitative Risk Assessment of Chemical Enterprises" [20]
(China Coal Industry Publishing House, 2013), the instantaneous mass flow that the leakage liquid flows
out through the holes of the storage tank is calculated by equation (1):

$$Q_m = \rho \times A \times C_a \times \sqrt{2 \times \left(\frac{P-P_a}{\rho} + g \times h_L\right)} \tag{1}$$

The leakage of a certain leak time period is generally calculated by using the instantaneous mass
flow at the initial moment of the leak and the leak time, however, the liquid level $h_L$ (above the leak hole
in the tank) changes with the leak time $t$, which causes the instantaneous mass flow $Q_m$ to change
accordingly when the tank leaks continuously. As a result, this method can not calculate the true
continuous leakage amount $M$ accurately during the leakage time period.

In order to achieve the fundamental goal of early warning and prevention, and realize the
development of emergency response plans, it is an urgent need to establish a relationship model between the continuous real-time release amount $M$ and the leakage time $t$.

### 2.2. Model Building

During the service period, corrosive ions in the hazardous chemicals solution cause corrosion to the inner wall of the storage tank, while corrosive medium in the atmosphere cause corrosion to the outer wall of the storage tank [21–22]. Under these conditions, the wall of the storage tank became locally thinned, therefore there may be a pitting hole on the wall and the surface breaks and leakage occurs because the sudden pressure drops at the wall after a certain time [23–25]. As a result, the two major factors affecting the continuous real-time leakage are the falling height of the liquid level in the tank and the flow speed of the liquid at the leaking hole. Basing on these two factors, the mathematical modeling process for real-time leakage is shown in Figure 1. The schematic diagram of tank leakage is shown in Figure 2.

![Mathematical modeling flow chart](image1)

**Figure 1.** Mathematical modeling flow chart.

![Schematic diagram of tank leakage](image2)

**Figure 2.** Schematic diagram of tank leakage.
2.2.1. Liquid Level Falling Velocity

The liquid level in the tank is continuously decreasing when leakage occurs. The falling liquid level velocity \( (v_1) \) in the tank could be characterized with the height of the liquid that is higher than the leaking point \( (h_L) \).

The liquid flow velocity \( v \) at the leak point is firstly investigated and characterized with \( h_L \). At the leaking point by the principle of mass conservation:

\[
Q_v = \frac{Q}{\rho} \quad (2)
\]

\[
Q_v = A \times v \quad (3)
\]

Equation (2) and Equation (3) are combined with Equation (1), thus the liquid flow rate \( (v) \) at the leak point would be:

\[
v = C_v \times \sqrt{2 \times \left( \frac{P - P_0}{\rho} + g \times h_L \right)} \quad (4)
\]

According to the basic law of conservation of mass, the quality of the liquid dropping in the tank should be the same as that of the leaking–out liquid through the leaking point:

\[
\rho \times A \times v = \rho \times A_i \times v_i \quad (5)
\]

Then the liquid level falling velocity \( (v_1) \) in the tank could be obtained by Equations (4) and (5):

\[
v_i = \frac{A}{A_i} \times C_v \times \sqrt{2 \times \left( \frac{P - P_0}{\rho} + g \times h_L \right)} \quad (6)
\]

2.2.2. Changing Rate of the Liquid Level Falling Velocity

The changing rate of the liquid level falling velocity is dependent on several factors, such as the diameter and height of the storage tank, the height of the liquid level in the storage tank, and the diameter of the leaking hole.

The change in the liquid level above the leaking point is taken into account for the leakage at any weak part of the tank:

\[
h_L = h - h_i - \Delta h \quad (7)
\]

Equation (6) is squared, and combined with (7), then the solution would be:

\[
\Delta h = \frac{\left( \frac{P - P_0}{\rho} + g \times h - g \times h_L \right)}{g} \times v_i^2 \quad \frac{2 \left( \frac{A}{A_i} \times C_v \right)^2 \times g}{2 \left( \frac{A}{A_i} \times C_v \right)^2 \times g} \quad (8)
\]

Assuming that the leakage time is \( t \), and the liquid level drop height \( \Delta h \) in the tank is found derivation for \( v_1 \):

\[
\frac{d \Delta h}{dv_i} = \frac{d \Delta h}{dt} \times \frac{dt}{dv_i} = \frac{v_i}{a_i} \quad (9)
\]

\[
\frac{d \Delta h}{dv_i} = \frac{v_i}{\left( \frac{A}{A_i} \times C_v \right)^2 \times g} \quad (10)
\]
The changing rate of the liquid level falling velocity in the storage tank is solved by the Equations (9) and (10):

\[ a_g = \left( \frac{A}{A_t} \times C_0 \right)^2 \times \frac{g}{A_t} \]  

\[ (11) \]

2.2.3. Continuous Real–time Release Model M

The liquid level falling velocity \( v_1 \) is obtained via indefinite integral of the leak time by the changing rate of the liquid level falling velocity in the storage tank \( a_g \):

\[ v_1 = \int a_g \times dt = \int g \times \left( \frac{A \times C_0}{A_t} \right)^2 \times dt = -\left( \frac{A \times C_0}{A_t} \right)^2 g \times t + C_1 \]  

\[ (12) \]

The integral constant \( C_1 \) is found by the boundary condition \( t = 0 \), \( v_1 \) is the maximum value, and \( \Delta h \) is zero, so:

\[ C_1 = \frac{A \times C_0}{A_t} \times \sqrt{2 \times \left( \frac{P - P_0}{\rho} + g \times (h - h_1) \right) + g \times t} \]  

\[ (13) \]

The liquid level falling velocity \( v_1 \) is obtained by Equations (12) and (13):

\[ v_1 = \frac{A \times C_0}{A_t} \times \sqrt{2 \times \left( \frac{P - P_0}{\rho} + g \times (h - h_1) \right) + \left( \frac{A \times C_0}{A_t} \right)^2 g \times t} \]  

\[ (14) \]

The integral constant \( C_2 \) is found by the boundary condition, if \( t = 0 \) and \( \Delta h = 0 \), then \( C_2 = 0 \), and:

\[ \Delta h = \frac{A \times C_0}{A_t} \times \sqrt{2 \times \left( \frac{P - P_0}{\rho} + g \times (h - h_1) \right) + \left( \frac{A \times C_0}{A_t} \right)^2 g \times t} \]  

\[ (\Delta h \leq h - h_1) \]

\[ (15) \]

In summary, the continuous real–time leakage amount \( M \) of the vertical tank body is obtained under the condition of \( M = \rho V = \rho A_t \Delta h \):

\[ M = \rho \times A \times C_0 \times \sqrt{2 \times \left( \frac{P - P_0}{\rho} + g \times (h - h_1) \right) + \frac{\rho \times g \times C_0^2 \times A_t^2}{2 \times A_t^2} \times t} \]  

\[ (\Delta h \leq h - h_1) \]

\[ (17) \]

2.3. Model Constraints and Verification

The model constraints of the continuous real–time leakage model \( M \) are as follows:

1. Before the time that the tank leakage occurs, that is, the leakage time \( t_{\text{leakage start}} = 0 \), the liquid level falling height \( \Delta h_{\text{start}} = h - h_1 = 0 \) and the continuous true leakage amount \( M_{\text{start}} = 0 \);

2. When the leakage is completed (all liquid above the leak orifice flows out), that is, when the leakage time \( t_{\text{leakage end}} \) reaches at a certain time, the liquid level descending height \( \Delta h_{\text{end}} = h - h_1 \) and the continuous true leakage amount \( M_{\text{end}} = M_{\text{max}} \);

3. During any time period \([t_i, t_{i+1})\), \( 0 \leq M_t < M_{i+1} \).
According to the actual liquid leakage and the model analysis, if the model constraints are established for the continuous real–time leakage amount calculation with the time \( t \) as the variable, the model is effective.

3. Model Application

3.1. Model of Software Construction

C# language is used to develop the corresponding software in order to facilitate the model solving and application. After the software functions are analyzed, the model input parameters and their logical relationships are determined, as well as the calculation output results and the graphic display functions, and the software programming is completed. Figure 3 shows the software development flow chart. Figure 4 shows the software application interface, (a) and (c) of Figure 4 are the whole process simulation amount, (b) and (d) of Figure 4 are the simulation amount of 200 s when the discharge coefficient is 0.65 and 0.82 respectively under the experimental application.

![Software development flow chart.](image-url)

**Figure 3.** Software development flow chart.
3.2. Experimental Application

3.2.1. Leakage Tanks and Main Parameters

A tank was specifically designed and tested in order to evaluate the application of the model and the operation of the software. The storage tank was made of PVC material and was a flat–bottom cylindrical storage tank. The diameter of the bottom is $D = 0.98\, \text{m}$, the total height is $H = 1.45\, \text{m}$, and the height of the cylindrical part is $H_1 = 1.04\, \text{m}$. The simulated leakage is through the small round holes. A plumb line was taken with a steel ruler and a level meter, and the position of the leak holes was calibrated from bottom up. The leakage hole diameter $d$ was measured by averaging three measurements using vernier caliper at three different angles through circle center. The leakage hole diameter $d$, the distance from the
leaking point to tank bottom \( h_1 \), the initial liquid level height \( h \), and the leakage hole shape are shown in Table 1. The leaking test liquid is tap water.

Table 1. Data sheet of tank leakage information.

<table>
<thead>
<tr>
<th>hole number</th>
<th>( h/\text{m} )</th>
<th>( h_1/\text{m} )</th>
<th>shape of leakage hole</th>
<th>( d/\text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.701</td>
<td>0.617</td>
<td>circular</td>
<td>0.0033</td>
</tr>
<tr>
<td>2</td>
<td>0.701</td>
<td>0.4677</td>
<td>circular</td>
<td>0.0034</td>
</tr>
<tr>
<td>3</td>
<td>0.701</td>
<td>0.2677</td>
<td>circular</td>
<td>0.0034</td>
</tr>
</tbody>
</table>

The discharge coefficient \( C_0 \) of 0.65 was generally applied for a circular leak hole, which was introduced in the book about accident analysis [26]. \( C_0 \) was not a clear value when tank body leaked in AQ3046–2013. However, it was clearly stated that the discharge coefficient was 0.62 for sharp orifices, 0.82 for rounded orifices, and 0.96 for straight orifices. So the theoretical values of \( C_0 \) are 0.65 and 0.82 to be compared with experimental value [7].

3.2.2. Experiment Requirement

Three repeated experiments were performed for each leak hole to better analyze the experimental results. A pressure sensing liquid level gauge was added to the test to facilitate real-time measurement of the leakage amount and real-time change of the liquid level. The relationship between the leakage time \( t \) and the real-time discharge amount \( M \) within a certain leakage period according to the simulation results of the model needs to be verified.

The leakage time step is 5 s during the experiments. The leaking liquid is collected and weighed in a 1000 mL beaker for 200 s. The leaking experiment site is shown in Figure 5.

Figure 5. Leaking experiment site.

4. Experimental Results and Discussion

4.1. Experimental Results

Each leakage orifice of No.1, No.2 and No.3 is tested for three times, and the discharge amount of every time step is collected, weighted and recorded. Then every graph of three real-time leakage amounts \( M_1, M_2 \) and \( M_3 \) are obtained. Then Figure 6, Figure 7 and Figure 8 illustrate the leakage amount...
of hole 1, 2, and 3 on time respectively. Figure 6 shows that $M_1$, $M_2$ and $M_3$ of hole 1 ($d = 0.0033 \text{ m}$, $h = 0.701 \text{ m}$ and $h_1 = 0.617 \text{ m}$) are close to each other, especially for the first two experiments, and the graph of $M_1$ is the largest among three discharging experiments. The amount of $M_1$ is $1783.88 \text{ g}$, $1760.22 \text{ g}$ and $1657.20 \text{ g}$ respectively when the leakage time is $200 \text{ s}$. Figure 7 shows that $M_1$, $M_2$ and $M_3$ of hole 2 ($d = 0.0034 \text{ m}$, $h = 0.701 \text{ m}$ and $h_1 = 0.4677 \text{ m}$) are nearly the same, especially for the first two experiments, and the graph of $M_2$ is the largest among three discharging experiments. The amount of $M_1$, $M_2$ and $M_3$ is $2967.12 \text{ g}$, $3043.92 \text{ g}$ and $2836.91 \text{ g}$ respectively when the leakage time is $200 \text{ s}$. Figure 8 shows that $M_1$, $M_2$ and $M_3$ of hole 3 ($d = 0.0034 \text{ m}$, $h = 0.701 \text{ m}$ and $h_1 = 0.2677 \text{ m}$) have almost no deviation, and the graph of $M_2$ is the largest among three discharging experiments. The amount of $M_1$, $M_2$ and $M_3$ is $4034.18 \text{ g}$, $4105.14 \text{ g}$ and $4065.25 \text{ g}$ respectively when the leakage time is $200 \text{ s}$.

**Figure 6.** Leakage amount curves of hole 1 with time ($d = 0.0033 \text{ m}$, $h = 0.701 \text{ m}$ and $h_1 = 0.617 \text{ m}$).
Figure 7. Leakage amount curves of hole 2 with time ($d = 0.0034$ m, $h = 0.701$ m and $h_1 = 0.4677$ m).

Figure 8. Leakage amount curves of hole 3 with time ($d = 0.0033$ m, $h = 0.701$ m and $h_1 = 0.2677$ m).

Figure 9 shows the structure of liquid level sensor. The actual liquid level differs by 5.5 cm since the pressure sensing element is 5.5 cm from the bottom of the liquid level gauge. Figure 10 reveals the relationship between the liquid falling level and the leakage time. The liquid level gauge shows that once the leakage occurs, the leakage amount cannot be judged based on the change of the level gauge’s readings.
4.2. Discussion

4.2.1. Comparative Analysis of Leakage

The average amount $M_a$ from three measurements of every discharging experiments is obtained to make a straightforward comparison. The positive deviation of the average by 20% ($M_{a+20\%}$), the negative deviation of the average by 20% ($M_{a-20\%}$), and the theoretical leakage amount $M_{t,0.65}$ (when $C_0=0.65$) and $M_{t,0.82}$ (when $C_0=0.82$) are illustrated in Figure 11, Figure 12 and Figure 13. $M_a$ and $M_t$ are in the intervals of $M_{a+20\%}$ and $M_{a-20\%}$ for hole 1, hole 2 and hole 3. Figure 11 shows that $M_a$, with the releasing time of 200 s, is much larger than $M_{t,0.65}$ but much closer to $M_{t,0.82}$, and $M_{t,0.65}$ is very close to $M_{a-20\%}$ when the tank body is continuously released by hole 1 ($d=0.0033$ m, $h=0.701$ m and $h_1=0.617$ m). Figure 12 reveals that $M_a$ is much larger than $M_{t,0.65}$, and close to $M_{t,0.82}$. And the deviation between $M_{t,0.65}$ and $M_{a-20\%}$ is slightly separated when tank body is continuously released by hole 2 ($d=0.0034$ m, $h=0.701$ m and $h_1=0.4677$ m). Figure 13 demonstrates that $M_a$ is much larger than $M_{t,0.65}$ but much closer to $M_{t,0.82}$.
Furthermore the deviation between $M_{t=0.65}$ and $M_{a-20\%}$ is almost the same when the tank body is continuously released by hole 3 ($d = 0.0033 \text{ m}, h = 0.701 \text{ m}$ and $h_1 = 0.2677 \text{ m}$).

**Figure 11.** Deviation leakage curves of hole 1 with time ($d = 0.0033 \text{ m}, h = 0.701 \text{ m}$ and $h_1 = 0.617 \text{ m}$).

**Figure 12.** Deviation leakage curves of hole 2 with time ($d = 0.0034 \text{ m}, h = 0.701 \text{ m}$ and $h_1 = 0.4677 \text{ m}$).
Figure 13. Deviation leakage curves of hole 3 with time \((d = 0.0033 \text{ m}, h = 0.701 \text{ m} \text{ and } h_1 = 0.2677 \text{ m})\).

Discharge coefficient \(C_0\) is an important factor for calculation of theoretical leakage amount. \(C_0\), as a theoretical discharge coefficient, is more suitable for the value of 0.82 under the condition studied in this paper. Figure 14 gives the relationship between \(M_a\) and \(M_t\) for leaking hole 1, 2 and 3. It could be straightly seen that the curves of \(M_a\) and \(M_{0.82}\) are almost completely coincident, which demonstrates that theoretical value of 0.82 for discharge coefficient \(C_0\) is perfect for hole 1 \((d = 0.0033 \text{ m}, h = 0.701 \text{ m} \text{ and } h_1 = 0.617 \text{ m})\). The curves of \(M_a\) and \(M_{0.82}\) have a little overlap, which states that theoretical discharge coefficient \(C_0\) should be corrected for hole 2 \((d = 0.0034 \text{ m}, h = 0.701 \text{ m}, h_1 = 0.4677 \text{ m})\). The curves of \(M_a\) and \(M_{0.82}\) have a slightly gap, which demonstrates that theoretical discharge coefficient \(C_0\) is 0.82 and could be used for hole 3 \((d = 0.0033 \text{ m}, h = 0.701 \text{ m} \text{ and } h_1 = 0.2677 \text{ m})\).

Consequently, the real–time leakage amount shows good linearity within 200 s leakage time. It can be seen that \(M_{0.65}\) for leakage hole 1 is very close to the average deviation \(M_{d-20\%}\) of the experimental leakage amount, while the \(M_i\) for leakage hole No. 2 and No. 3 have a certain deviation from \(M_{d-20\%}\). All the \(M_i\) of three holes are less than its \(M_{0.82}\) but closely to its \(M_{0.82}\), which demonstrates the validity of the model.
4.2.2. Effect of Liquid Level above the Leak Hole on Leakage Stability

The effect of the liquid level above the leak orifice on the leak hole is mainly reflected in the pressure at the leak hole. Under the same meteorological conditions, the pressure at the leakage hole is \( P - P_0 + \rho gh_l \) when the original liquid level \( h \) in the storage tank is unchanged and the distance between the leakage hole and the ground \( h_1 \) is different. The pressure at the leak hole is \( \rho gh_l \) because the liquid saturated vapor pressure \( (P - P_0) \) is negligible for the regular pressure tank. The experimental leak amount \( M \) of different leak holes varies with the instantaneous continuous flow velocity at the leak hole changes because of the pressure.

The liquid level height \( h_l \) above the leakage hole increases as the height \( h_1 \) of the leakage hole decreases, the liquid level change \( \Delta h \) in the storage tank will decrease slowly after the leakage occurs when the original liquid level \( h \) is unchanged, so the change of pressure generated \( (\rho gh_l) \) is small. Therefore, the smaller the height \( h_1 \) of the leakage hole is, the more stable the instantaneous continuous flow velocity is and the larger leakage rate is. Obviously, during any time of the leakage, the real–time leakage amount \( M_a \) of the No. 1 hole is the smallest, while the \( M_a \) for the No. 3 hole is the largest (Figure 14). This is verified by leak test data for holes NO. 1, 2 and 3.

4.2.3. Effect of Discharge Coefficient \( C_0 \) on Leakage

The discharge coefficient \( C_0 \) represents the dimensionless constant [27], which is obtained from the complex function of the Reynolds number of the flow and the leak bore diameter [5, 28, 29, 30, 31]. The Reynolds number is defined as \( Re = \rho v d / \eta \), where \( \rho \) is the liquid density, \( v \) is the liquid flow rate at the leak hole, \( d \) is the release hole diameter, and \( \eta \) is the dynamic viscosity coefficient of the liquid. Because the discharge coefficient \( C_0 \) is affected by the Reynolds number and the diameter of the leakage hole, the
flow velocity of the leakage orifice changes continuously due to these factors. The original liquid level \( h \) and the height \( h_1 \) are different from each other, which leads to the corresponding Reynolds number \( Re \) being different, so the discharge coefficient \( C_0 \) is a non-constant value. In summary, \( C_0 \) should be adjusted according to the situation. In this paper, \( C_0 \) is 0.82 for calculation of the theoretical leakage amount \( M_t \).

5. Conclusions

This paper focuses on the calculation of continuous real-time leakage amount after liquid hazardous chemicals vertical tank releases. Through mathematical modeling, programming the model, and experimental verification, the conclusions are obtained as follows:

(1) The mathematical model of continuous real-time release \( M \) and leakage time \( t \) is established by the principle of mass conservation, which can improve the accuracy of continuous real-time release in any leakage period after the tank body leaks.

(2) By experimental analysis of repeated leakage tests, the more stable the flow rate and the larger the leak rate are under the condition that the higher the liquid level above the leakage hole \( (h_L) \) is, the greater the pressure on the leak hole is and the smaller the pressure changes at the leaking hole is. All the \( M_a \) of three holes are less than its \( M_{0.82} \) but closely to its \( M_{0.82} \), the experimental results states that the established model is effective.

(3) The discharge coefficient \( (C_0) \) affects the accuracy of calculating leakage amount, which may lead to deviations between \( M_t \) and \( M_a \). The calculation accuracy of the continuous real-time leakage amount \( M \) can be realized when the value of discharge coefficient is appropriate, and the reliability of early warning prevention scheme can be provided for enterprise and government emergency rescue.

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Nomenclature

\( M \) continuous real-time leakage amount  
\( Q_m \) mass flow  
\( Q_v \) volume flow  
\( \rho \) liquid density  
\( A_1 \) bottom area of the tank  
\( A \) area of leaking hole  
\( C_0 \) discharge coefficient
\[ P \] liquid pressure in the tank \[ P_0 \] environmental pressure \[ g \] gravitational acceleration \[ h \] original liquid height in the tank before leakage \[ h_1 \] distance from the leaking point to tank bottom \[ h_L \] liquid height above the leaking hole \[ \Delta h \] height at which the liquid level drops after the tank leaks \[ v \] flow rate of the liquid at the leak hole \[ v_1 \] falling liquid level velocity in the tank \[ a_1 \] changing rate of the liquid level falling velocity in the storage tank \[ t \] leakage time \[ C_1 \] internal constant \[ C_2 \] internal constant \[ V \] total volume of liquid leaked \[ D \] tank bottom diameter \[ H \] total tank height \[ H_1 \] cylindrical part height \[ d \] leakage hole diameter \[ M_1 \] continuous leakage amount of the first experiment of every hole \[ M_2 \] continuous leakage amount of the second experiment of every hole \[ M_3 \] continuous leakage amount of the third experiment of every hole \[ M_a \] average amount of the three experimental leakage of every hole \[ M_t \] theoretical leakage calculation of every hole \[ M_{0.65} \] theoretical leakage calculation \((C_0 = 0.65)\) of every hole \[ M_{0.82} \] theoretical leakage calculation \((C_0 = 0.82)\) of every hole \[ M_{a+20\%} \] average value of the experimental leakage is positive by 20 \% \[ M_{a-20\%} \] average value of the experimental leakage is negative by 20 \% \[ Re \] Reynolds number \[ \eta \] dynamic viscosity coefficient of the liquid

### References


