Discussion on Ventilation Measures and Effects of the Cistern in Shanghai Xinhongxia Residential Quarter

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Abstract: Focusing on the ventilation problems of cisterns in confined space operations, this study takes the cistern of Building 1, Xinhongxia Residential Quarter in Shanghai as the research subject. Comparative experiments were carried out to investigate the effects of natural ventilation and mechanical ventilation. Adopting equipment such as a pump-suction four-in-one gas detector and axial flow fan, the changes of oxygen concentration in the cistern under different ventilation modes were measured. The results show that mechanical ventilation has significant advantages in improving the oxygen level inside the cistern, which can provide a reference for the selection of ventilation schemes for similar confined spaces.

Keywords: Cistern; Ventilation Measures; Ventilation Effect; Confined Space

1. Introduction

In recent years, confined space operation has become a key focus in the work safety field due to its particularity and high risk[1,2]. Such operating environments are characterized by enclosed spaces and poor ventilation, which easily cause the accumulation of toxic and harmful gases and further poses risks such as poisoning and suffocation[3-5]. On November 6, 2023, the Ministry of Emergency Management of the People's Republic of China issued the Safety Regulations for Confined Space Operations in Industrial and Trade Enterprises (Order No. 13). This regulation redefines confined spaces in a more detailed manner and puts forward corresponding requirements for risk identification, prevention and control measures. Among relevant issues, oxygen concentration control in narrow and enclosed cisterns is both critical and difficult. At present, there is a lack of targeted research focusing on such scenarios, which directly compares two mainstream ventilation methods (natural ventilation and mechanical ventilation) with oxygen concentration as the core indicator. Therefore, this paper carries out relevant research. Based on the comparative results of quantitative experimental simulation, it discusses ways to improve the ventilation efficiency of such confined spaces, so as to prevent poisoning and asphyxiation risks from the source.

2. Research Object and Experimental Equipment

2.1 Research Object

This study takes the cistern of Building 1, Xinhongxia Residential Quarter in Shanghai as the research object. The cistern is $2.8m$ in height, $3.8\ m$ in net width and $5\ m$ in depth, with a volume of $53.2\ m^3$ and a ventilation opening area of $0.336m^2$. There is no radiation source of toxic and harmful gases inside the cistern. However, the cistern is equipped with only one ventilation opening, which is poorly positioned at the upper-right corner. The interior of the cistern features high temperature and high humidity with an enclosed and narrow spatial structure. Oxygen concentration inside may decline due to oxidation of metal components, microbial decomposition and oxygen consumption by chemical agents, which brings potential safety risks. In accordance with the definition criteria for confined spaces specified in Order No.13, the cistern conforms to the technical characteristics of easily forming an oxygen-deficient environment and poses hidden dangers for operation safety.

2.2 Experimental Equipment

One pump-suction four-in-one gas detector is adopted, which has completed zero-point calibration and indication calibration to ensure the reliability of measured data. One axial flow fan equipped with air duct is used, with model SFGNO2.5-2R, rated power $0.25\ KW$, total pressure $215Pa$, and air volume $2100m^3/h$.

3. Research Methods

3.1 Study on the Variation of Oxygen Concentration during Natural Ventilation of the Cistern

(1) The variation of oxygen concentration under natural ventilation is calculated by semi-empirical formula.

Taking the confined space emergency drill of the company as an opportunity, after the enclosed cistern is opened, the gas detector is immediately adopted to measure the initial oxygen concentration(%) denoted as C_0 at Point A, which is 2.0 m directly below the ventilation opening (as shown in Figure 1 and Figure 2). According to the characteristic parameters of the cistern, the ventilation rate at each time node of t=3,t=6,…,t=30 minutes after natural ventilation is calculated based on the semi-empirical formula of fluid mechanics. Combined with the ventilation rate and the oxygen concentration of internal and external air before mixing, the average oxygen concentration of mixed gas under the ideal uniform mixing condition is further calculated[6].

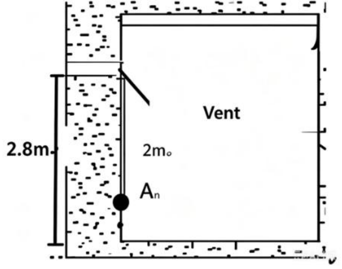


Figure 1. Profile of Location of Detection Point A in the Cistern

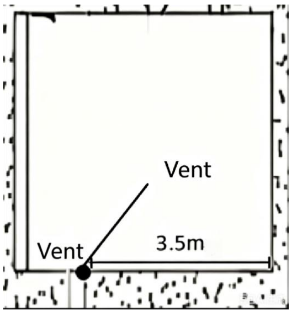


Figure 2. Plan View of Location of Detection Point A in the Cistern

(2) Collect the measured values of oxygen concentration by the static time-series measurement method.

After measuring the initial oxygen concentration (%) at Point A with the detector, the oxygen concentration of the cistern is collected at the same position every 3 minutes starting from t=0. The recorded data $C(t)$ are adopted to obtain the variation trend of oxygen concentration during the natural ventilation process of the cistern.

3.2 Variation of Oxygen Concentration in the Cistern during Mechanical Ventilation

During a subsequent cistern cleaning operation, an axial flow fan was adopted to conduct mechanical ventilation for the cistern. The oxygen concentration was continuously measured at the same Detection Point A by the gas detector. By comparing with the measured data under natural ventilation, the effect of mechanical ventilation was clarified.

3.3 Summary and Analysis of Experimental Results

In-depth analysis was carried out by comparing the calculated and measured oxygen concentration values under natural ventilation, as well as the measured oxygen concentration data during mechanical ventilation. The research results can provide a reference for the selection of ventilation schemes for similar confined spaces under specific conditions with identical or similar structural conditions and environmental parameters.

4. Research Process

4.1 Detection of Oxygen Concentration inside the Cistern and Ambient Air

Immediately after opening the enclosed cistern, the initial oxygen concentration C_0 was measured at Point A using the gas detector. The measured initial oxygen concentration C_0 was 19.9%, and the oxygen concentration of the ambient air was 20.9%.

4.2 Calculation of Natural Ventilation Rate of the Cistern Based on Initial Conditions and Cistern Characteristics

In the natural ventilation process, the Reynolds number is obviously lower than 2300, and the air flow belongs to the laminar flow state. The ventilation rate is driven by thermal pressure difference and wind pressure difference, and the core formula is given as follows:

(1) Natural ventilation rate under the action of wind pressure difference:

$$Q_W=C_W\cdot A_W\cdot\sqrt{2\cdot\frac{\Delta P_w}{\rho}} \qquad (1)$$

Q_w : Ventilation volume generated by wind pressure difference (m^3/s)

C_w : Discharge coefficient of the wind-side ventilation opening (related to the shape and layout of the air inlet and outlet. The ventilation opening of this cistern is a free outlet with symmetrical boundaries on both inner and outer sides, and the value is appropriately taken as 0.65)

A_w: Effective area of the wind-side ventilation opening(m^2), which is $0.336m^2$ for this cistern

ΔP_w: Wind pressure difference(Pa),

$$\Delta P_w = 0.5 \cdot \rho \cdot v^2 \cdot C_p \tag{2}$$

v denotes the outdoor wind speed, C_p denotes the aerodynamic coefficient. For the unobstructed indoor doorway at this location, the value is set as 0.5.

ρ: Air density (approximately $1.186kg/m^3$)

According to Bernoulli's principle, the energy conservation of an ideal fluid in flow can be simplified as that the sum of static pressure and kinetic energy of the fluid remains constant.

$$P + \frac{1}{2}\rho v^2 = constant \tag{3}$$

Therefore, a higher fluid flow velocity corresponds to a relatively lower static pressure. In accordance with the Beaufort wind scale, the wind speed difference between the inside and outside of the cistern is approximately $1m/s$.

The calculated pressure difference between the interior and exterior of the cistern is:

$$\Delta P \approx 0.3Pa \tag{4}$$

Substituting gives:

$$Q_w = C_w \cdot A_w \cdot \sqrt{2 \cdot \frac{\Delta P_w}{\rho}} = 0.154m^3/s \tag{5}$$

(2) Natural ventilation rate under the action of thermal pressure difference:

$$Q_t = C_t \cdot A_t \cdot \sqrt{2 \cdot \frac{\Delta P_t}{\rho}} \tag{6}$$

The thermal pressure difference is generated by the air density difference between indoor and outdoor environments caused by temperature difference, and the calculation formula is as follows:

Q_t : Ventilation volume induced by thermal pressure difference (m^3/s)

C_t : Discharge coefficient of the ventilation opening on the thermal pressure side (the same as C_w, taken as 0.65)

A_t: Effective area of the ventilation opening on the thermal pressure side (m^2), equal to A_w with a value of $0.336m^2$.

ρ : Air density. According to the ideal gas equation, the outdoor air density $\rho_{out} = 1.186kg/m^3$ (ambient temperature outside the cistern: 27°C), and the indoor air density $\rho_{in} = 1.153kg/m^3$ (internal temperature of the cistern: 35°C).

Thermal pressure difference(Pa):

$$\Delta P_t = gh(\rho_{out} - \rho_{in}) \tag{7}$$

g is the gravitational acceleration; h is the height difference between the air inlet and outlet. For this cistern, h refers to the height difference between the upper and lower edges of the single ventilation opening, which is $0.58m$.

The density difference:

$$\rho_{out} - \rho_{in} = \frac{0.033kg}{m^3} \tag{8}$$

$$\Delta P_t \approx 0.19Pa \tag{9}$$

Substituting into the formula gives:

$$Q_t = C_t \cdot A_t \cdot \sqrt{2 \cdot \frac{\Delta P_t}{\rho}} = 0.123m^3/s \tag{10}$$

(3) Total natural ventilation rate:

When wind pressure difference and thermal pressure difference act simultaneously, the total ventilation rate shall be superimposed or offset according to their directions (same direction or opposite direction). In practical calculation, correction should be made combined with specific working conditions, such as vent position and airflow direction. In the natural ventilation of this cistern, the airflow directions driven by wind pressure difference and thermal pressure difference are opposite (as shown in Figure 3 and Figure 4). Under simplified conditions, the algebraic difference between the two can be adopted for approximation.

$$Q_{total} = Q_w - Q_t = 0.031m^3/s \tag{11}$$

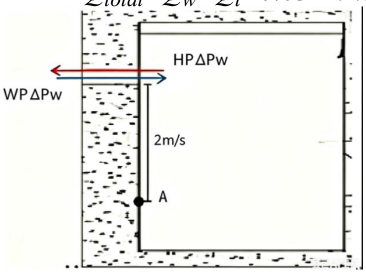


Figure 3. Profile of Wind Pressure Difference and Thermal Pressure Difference in the Cistern

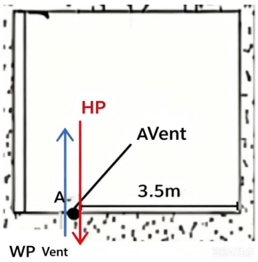


Figure 4. Profile of Wind Pressure Difference and Thermal Pressure Difference in the Cistern

4.3 Summarize the Calculated and Measured Values of Oxygen Concentration in the Cistern at Each Time Point

According to the total ventilation rate Q_{total}, calculate the ventilation volume at an interval of every 3 minutes after natural ventilation t=3,t=6,…,t=30min. Based on the weighted average calculation method of ventilation volume and the oxygen concentration of internal and external air before mixing, the average oxygen concentration inside the cistern at different times is calculated under the ideal uniform mixing condition. Meanwhile, the actual oxygen concentration in the cistern is detected every 3 minutes by the gas detector (as shown in Table 1 below).

Table 1. Calculated and Measured Variation of Oxygen Concentration Corresponding to Natural Ventilation Volume

Time (min)	**T3**	**T6**	**T9**	**T12**	**T15**	**T18**	**T21**	**T24**	**T27**	**T30**
Ventilation Volume (m^3)	5.58	11.16	16.74	22.32	27.9	33.48	39.06	44.64	50.22	55.8
Calculated Oxygen Concentration (%)	20.0	20.07	20.1	20.2	20.24	20.27	20.31	20.35	20.38	20.42
Measured Oxygen Concentration (%)	20.2	20.27	20.55	20.7	20.8	20.9	20.9	20.9	20.9	20.9

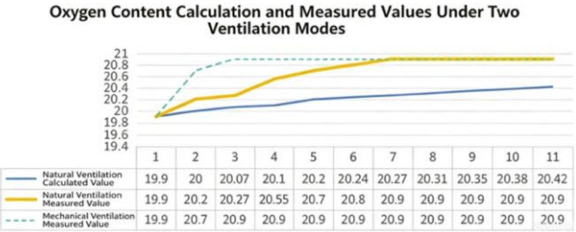
4.4 Collection of Oxygen Concentration Variation Data during Mechanical Ventilation of the Cistern

Taking a subsequent cleaning operation of the cistern as an opportunity, an axial flow fan was adopted for mechanical ventilation, and the oxygen concentration at Detection Point A was measured and recorded at different time intervals. In the process of mechanical ventilation, the Reynolds number of airflow is significantly higher than 2300, presenting a turbulent flow state with high randomness and instability of gas molecules. In a highly chaotic natural system, pursuing mathematical completeness may deviate from the essence of engineering practice. Therefore, this study abandons the establishment of a mathematical model and directly records the variation of oxygen concentration under mechanical ventilation through field measurement, as shown in Table 2.

Table 2. Measured Oxygen Concentration of Cistern under Mechanical Ventilation

Time (min)	**T0**	**T3**	**T6**	**T9**	**T12**	**T15**	**T18**	**T21**	**T24**	**T27**	**T30**
Measured Oxygen Concentration (%)	19.9	20.7	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9

4.5 Summarize the data



	1	2	3	4	5	6	7	8	9	10	11
Natural Ventilation Calculated Value	19.9	20	20.07	20.1	20.2	20.24	20.27	20.31	20.35	20.38	20.42
Natural Ventilation Measured Value	19.9	20.2	20.27	20.55	20.7	20.8	20.9	20.9	20.9	20.9	20.9
Mechanical Ventilation Measured Value	19.9	20.7	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9

Figure 5. Variation Trend of Oxygen Concentration Reflected by Experimental Data under Two Ventilation Modes

The experimental values under the two ventilation modes are organized in Figure 5 to illustrate the variation trend of oxygen concentration.

5. Experimental Data Analysis

5.1 Analysis on the Causes of Differences between Calculated and Measured Values of Natural Ventilation

According to the experimental data, the measured growth values of oxygen concentration under natural ventilation are obviously higher than the calculated values. The main possible reasons are analyzed as follows:

(1) Deviation between actual conditions and ideal assumptions of the calculation model. The original calculation model adopts a laminar flow model under highly ideal assumptions such as "uniform gas mixing" and "constant ventilation rate". Multiple parameters are selected by empirical coefficients with limited accuracy, and each parameter presents complex dynamic changes in the actual ventilation process[7]. In this calculation, the oxygen concentration is simplified by the weighted average of indoor and outdoor gas volume and oxygen content, without adopting the molar quantity of oxygen molecules which is more in line with the actual situation.

(2) Influence of measurement position. Restricted by technical conditions, the detector cannot be placed deep inside the cistern. Consequently, Detection Point A is close to the ventilation opening rather than the most unfavorable ventilation position. The measuring point preferentially contacts fresh air with high

oxygen content, making the rising rate of local measured oxygen concentration much faster than the spatial average level, which leads to an overestimation of the overall oxygen recovery rate.

(3) Influence of unconsidered local airflow. In the actual ventilation process, local strong airflow may exist inside the cistern. Transient external gusts, gaps at the ventilation opening, and eddy currents formed by internal obstacles can all accelerate the replacement of internal air with external fresh air, resulting in an actual inflow rate of fresh air higher than the calculated value.

(4) Influence of unconsidered additional heat sources. Heat generated by operating equipment inside the cistern causes an uneven internal temperature distribution. This produces a stronger thermal pressure ventilation effect between the interior and exterior, further accelerating the inflow speed of fresh air.

5.2 Comparison of Ventilation Effect between Mechanical Ventilation and Natural Ventilation

The measured variation data of oxygen concentration under mechanical ventilation show that the oxygen concentration rises rapidly from 19.9% to 20.7% within the first 3 minutes under mechanical ventilation. It further increases to 20.9%, consistent with the ambient air oxygen concentration, within the first 6 minutes and then tends to be stable. It indicates that sufficient replacement of internal air is realized after about 10 minutes of mechanical ventilation. The measured results verify that the axial flow fan possesses effective air exchange capacity, which can keep the oxygen concentration above the safety limit and meet the operational environmental requirements for confined space work.

5.3 Improvement Suggestions Based on Experimental Analysis

Experimental Analysis 1: The natural ventilation process is affected by the strong coupling of multiple parameters, including instantaneous wind speed fluctuation $V(t)$, wind direction angle $\theta(t)$, ambient temperature difference $\Delta T(t)$, and opening turbulence characteristics. In enclosed cisterns with limited space, complex structure, narrow or remote ventilation openings, the airflow movement law is significantly different from that in conventional spaces, resulting in a non-simple linear relationship between the numerically calculated values and the measured values.

Suggested Measures: Independent evaluation of oxygen concentration must be conducted for each different cistern, and other similar cases shall not be applied blindly. The oxygen concentration of all such confined spaces shall not be replaced by calculation with measurement. Before each confined space operation, the process must be strictly followed: after ventilation, detection shall be carried out, and entry into the space for operation is permitted only after all gas indicators are confirmed to be qualified through detection.

Experimental Analysis 2: The effect of natural ventilation is restricted by the position of ventilation openings and external environmental conditions, presenting problems of insufficient stability and low efficiency. The area close to the ventilation openings can achieve relatively optimal ventilation effect, but in the internal area far from the ventilation openings, due to the uneven distribution of flow field and local eddy currents (dead zones), the oxygen concentration may be significantly lower than the measured value at Point A mentioned in this paper. In addition, the oxygen consumption behavior of operators when entering the confined space will lead to a continuous decrease in oxygen concentration.

Suggested Measures: When arranging operators to enter the confined space for operation, the operators must wear portable gas detectors before entering the operation area, and maintain continuous ventilation and real-time monitoring of gas concentration throughout the operation process. If the operation is interrupted, before personnel re-enter, comprehensive ventilation must be re-implemented, and personnel are only allowed to enter the operation area after the gas detection indicators meet the safety standards.

Optimization Suggestions: Install additional intelligent gas monitoring points in poorly ventilated areas (dead zones) inside the cistern to build a sensor network for dynamically monitoring the variation of oxygen concentration. It is recommended to adopt Internet of Things transmission technology to synchronize real-time monitoring data to the central control system[8]. When the oxygen concentration at any monitoring point drops below the safety threshold of 19.5%, the system automatically triggers an alarm mechanism.

Combined with regular emergency drills, the safety of the operation process can be maximally guaranteed.

Experimental Analysis 3: Compared with natural ventilation, the mechanical ventilation system has obvious advantages in raising the oxygen concentration in confined spaces. However, equipment layout may form a local jet flow field, which restricts the uniform diffusion of gas and creates ventilation dead zones, a phenomenon that deserves sufficient attention[9-11]. According to relevant standards, the oxygen concentration of 19.5% is only the minimum limit for safe operation. For personnel engaged in physical labor, a working environment with higher oxygen concentration should be provided to establish necessary safety redundancy and ensure operational safety.

Suggested Measures: For confined spaces with complex structures, poor ventilation conditions or limited space dimensions, forced mechanical ventilation must be adopted, and continuous ventilation shall be maintained throughout the whole operation process.

Optimization Suggestions: To address ventilation dead zones and local oxygen deficiency risks in confined spaces, additional agitation fans can be installed to enhance air disturbance. The structure of air duct outlets should be optimized by adopting a flared opening design to improve the discharge coefficient.

6. Conclusion

The variation of oxygen concentration in confined spaces is affected by multiple influencing factors. For any confined space, field measurement shall not be replaced by theoretical calculation. Confined space operations must strictly follow the procedure of ventilation first, inspection second, operation last. Moreover, mechanical ventilation should replace natural ventilation, with the ventilation duration maintained for no less than half an hour. This ensures sufficient air replacement inside the confined space and keeps the oxygen concentration up to the safety threshold.

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