Research on Explosive Characteristics of Combustible Gas within the Restricted Space in Wells

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Abstract. The explosion of the combustible gas within the restricted space in the city wells will endanger the people’s life and fortune. The syncretic gas detector of MX4 and MX6 are used in this study to detect the harmful gas in the well. The result shows that the main harmful gases are mainly CH₄, H₂S and CO₂, and their content range is given. Then the explosion test of the combustible gas is done in the spherical explosion vessel of 20L in volume in the lab, which studies the effect of the content of the methane and CO₂ on the explosion maximum pressure and its increase rate. Finally, FLACS code is adopted to study the effect of the inert gas CO₂ in the well on effectively restricting the methane combustion and explosive reaction. It is found that CO₂ has the restrict effect on the methane explosion.

1. Introduction

In recent years, our city scale has been grown larger and larger with the rapid development of the urban construction. Meanwhile the underground pipeline system of the city is becoming complex and enormous, which is called the city lifeline. However, lots of combustible gas even hazardous gas is unceasingly accumulated in the city wells at the same time, which will produce very destructive explosive reaction when it encounters the ignition source. Therefore, the operational state of the city well system not only reflects the feature of the whole city but also closely relates to the safety of the citizens and their property.

Because lots of slush and household garbage are prolonged kept in the city wells, a series of combustible and hazardous gases such as CH₄, H₂S, CO₂, CO and SO₂ are produced because they are decomposed by the microbe [1]. Lots of these gases are accumulated in the wells, and the significant impact on the safety of the citizens and their property will occur when it encounters the ignition source. According to the statistic results, the blasting incidents in the well often happen in recent years. In seriousness, tens of accidents happen which causes the direct and indirect economic loss even to several hundred million RMB [2]. So, it is no time to delay to study the explosion characteristic of the combustible gas within the restricted space in wells. Through the intensive study on the explosion characteristic, parameter change law and its specific effect factor, the effective countermeasures are obtained which can prevents the explosion of the gas within the restricted space in the well to happen. Meanwhile the corresponding theory is put forward to ensure the safety of the citizens and their property, which will fundamentally provide the safeguard for the urbanization construction.

Many researchers studied this issue with theory, experiment and numerical simulation. Yu [3] studied the flame propagation law of gas explosion on different hollow square obstacles. Cui [4] studied...
factors affecting the explosion release of methane-air mixture in the containers by experiments. Gao [5] made a comparative study on the occurrence and causes of gas explosion in coal mines between China and the United States. Xu [6] proposed a new method to suppress gas explosion by using a charged water mist explosion simulation system. Pei [7] carried out an experimental study on synergistic suppression of gas explosion in ventilation ducts by nitrogen and superfine water mist. Chyż [8] plutonium proposed the building load model of indoor gas explosion and established the incremental formula of explosion simplified function. Yin [9] analyzed the coal mine gas explosion accident and its unsafe behavior characteristics from 2000 to 2014 in China. Yang [10] used computational fluid dynamics to study the simulation of gas explosion in an electrostatic precipitation.

Therefore on basis of the previous research, the ingredient detection of the gas in the well is firstly investigated to determine the main ingredients of the gas in the well, and then the explosion effect under different conditions in the well is simulated with FLACS code to investigate the effect of many factors on the explosion characteristic of the combustible gas within the restricted space in the well.

2. Detection of the Gas in the Well and its Ingredients
Take one college of Beijing as an example, and the gas ingredient detection is done in some representative regions including the complex area, dining area, education area and apartment area. The high accurate and advanced gas detector of iBrídMX4 and iBrídMX6 produced in America is selected in this study. The detection results in different areas are shown in Tab.1.

Table 1. Detection result of the gas concentration

|                 | H₂S/ppm | CH₄/LEL | CO₂/VOL |
|-----------------|---------|---------|---------|
| Complex area    | 0.2~34.3| 0~22    | 0~1.81  |
| Dining area     | 1.6~52.5| 0~24    | 0~2.71  |
| Education area  | 1.2~1.8 | 0~27    | 0~2.50  |
| Apartment area  | 2.9~61.6| 0~32    | 0~2.31  |

3. The Explosion Test of the Combustible Gas in the Spherical Explosion Vessel

3.1. Experiment Equipment
The experiment equipment consists of the spherical explosion vessel of 20L in volume and the controlling and data collection system. Through the inspection window, the flame effect in the explosion chamber can be inspected. The piezoelectric pressure sensors are fixed at the internal face of the vessel, which can measure the dynamic pressure produced in the explosion.

![Figure 1: 20L spherical experimental device](image)

3.2 Experimental Procedure
(1) Gas preparation
According to the Dalton’s laws of partial pressure, the absolute pressure of the mixed gas equals to the sum of that of each one. The pressure balance method is adopted to make the mixed gas in this experiment, and the calculation formulae are shown as (1) and (2).

\[ P = \sum P_i \]  
\[ P_i = P \phi_i \]

where, \( P \) is the absolute pressure of the mixed gas, Pa; \( P_i \) is the absolute pressure of the \( i \)th gas of the mixed gas, Pa; \( \phi_i \) is the volume percentage of the \( i \)th gas of the mixed gas, \%.  

From (1) and (2), the partial pressure of each gas can be calculated, and according to the result, each gas is injected and stirred for a few minutes, finally the mixed gas is done.

(2) Detection of the ignition source

After the explosion experiment, the ignition source needs to change and it is necessary to detect the performance of the ignition source. Detecting the pressure produced by the ignition source itself after pumping the explosion vessel into vacuum, and it value range is about 0.11±0.01MPa.

(3) Gas tightness detection of the apparatus

After detecting the performance of the ignition source, the gas tightness detection of the experiment apparatus must be done in order to ensure the good gas tightness of the apparatus. It can prevent the bad results because of the unsuitable gas tightness detection of the apparatus.

(4) Gas replacement

Firstly turn on the inflow and drain taps, and then incessantly pour the pure air into the reaction system to clean the explosion chamber. Then blowing the explosion vessel with the mixed gas through the inflow tap.

(5) Pouring the mixed gas

After pumping the explosion vessel into vacuum, pouring the mixed gas into the explosion chamber through the inflow tap. During it, monitoring the pressure of the explosion chamber till it reaches the required value, and turning off the inflow tap.

(6) Ignition

After turning off the inflow tap, we should fully and evenly make the gas mixed for 50ms. After that, ignition is made. The pressure sensors start to record the pressure and the test result is done by the data-collecting system.

3.3 Experiment Results and Analysis

Since the H2S content is very small in the test, it is negligible at the experimental dose, so H2S is not used in this experiment. The gases used in this experiment are mainly CH4 and CO2.

(1) Lower explosion limit test of CH4 and CO2 mixed gas

Four groups of experiments are done in the spherical explosion vessel of 20L in volume in the lab to test the lower explosion limit test of CH4 and CO2 mixed gas when the content of CO2 are 3%, 6%, 9% and 12%. The setting ratio of the mixed gas adopted in the experiment is slightly different from that in reality. Recording every gas explosion case and obtaining the following results. When 3%, 6%, 9% and 12% of CO2 is pouring into the blast vessel, the lower explosion limit test of CH4 are 4.3%, 4.8%, 5.2% and 5.9%.

(2) The effect of the methane content on the explosion characteristic of the combustible gas

The explosion experiment is done on CH4 and air mixed gas with content of 5.5%, 7.5%, 9.5%, 11.5% and 13.5% respectively at the normal pressure and temperature. After the explosion, the explosion pressure increased rapidly, and then the pressure of explosion began to decrease because of the loss of heat in practice. The pressure and its climbing speed both firstly increase and then decrease.
The maximum explosion pressure $P_{\text{max}}$ and the maximum climbing speed of the pressure $(dp/dt)_{\text{max}}$ are obtained shown in Fig.2 and Fig.3. It can be found that the explosion is weak when the content of methane in the mixed gas reaches the lower explosion limit. The waveform produced by the explosion shows that there is a long precursor pressure wave region during the explosion, and the pressure in the positive and negative pressure region is little.

![Figure 2: The maximum explosive pressure of CH$_4$](image1)

![Figure 3: The maximum climbing speed of the pressure of CH$_4$](image2)

When the content of CH$_4$ is 5.5% and 13.5%, $P_{\text{max}}$ is 0.46MPa and 0.44MPa, and $(dp/dt)_{\text{max}}$ is 3.2MPa·s$^{-1}$ and 2.8 MPa·s$^{-1}$ respectively. The explosion is relatively strong when the content of methane in the mixed gas is in the middle of the lower explosion limit.

3) The effect of CO$_2$ on the explosion characteristic

From the detection result of the gas in the well, it can be known that the maximum content inert gas ingredient in the well is CO$_2$. Therefore CO$_2$ is selected to do the explosion test to study the effect of CO$_2$ on the maximum explosion pressure $P_{\text{max}}$ and the maximum climbing speed of the pressure $(dp/dt)_{\text{max}}$. Five mixed gas with different CO$_2$ content of 0%, 5%, 10%, 15% and 20%, and different CH$_4$ content of 5%, 6%, 8%, 10% and 12% are used respectively in the experiment. The experiment results are shown in Tab.2 and Tab.3. The following conclusions can be obtained.

1) Fixing the content of CH$_4$ in the mixed gas and increasing the content of CO$_2$ from 0 in every group of experiments, we can find that the maximum explosion pressure of the mixed gas of methane and air constantly increases. It can be known that CO$_2$ can make the explosion pressure of the mixed gas and air decrease, which has certain explosion suppression. Meanwhile it can be seen from Tab.1 that the explosion pressure is evidently affected by CO$_2$ and the decreasing extent of the pressure is rather large when the content of CH$_4$ is 10% and 12% respectively.

2) Fixing the content of CO$_2$ in the mixed gas and increasing the content of CH$_4$ from 5% in every group of experiments, we can find that the maximum explosion pressure of the mixed gas of methane and air all increase firstly and then decrease. The change trend is in accordance with that without CO$_2$. Similarly, accordingly the maximum explosion pressure of CH$_4$ and air mixed gas decrease with increasing the content of CO$_2$.

3) When there is CO$_2$ pouring into the system, the maximum explosion pressure of the mixed gas of methane and air reaches 0.75MPa when the content of CH$_4$ increases to 10%. At this moment, pouring CO$_2$ into the system from its content being 5%, it can be found that the maximum explosion pressure of the mixed gas of methane and air occurs when the content of methane is 8%. The decrease from 10% to 8% indicates that CO$_2$ has the function of explosion suppression.

4) Fixing the content of CH$_4$ in the mixed gas and increasing the CO$_2$ content from 0 in every group of experiments, we can find that the maximum climbing speed of the explosion pressure of the mixed gas of methane and air constantly decreases. It can be known that CO$_2$ can make the maximum climbing speed of explosion pressure of the mixed gas and air decrease, which has certain explosion suppression. Meanwhile it can be seen from Fig.2 that the explosion pressure is evidently affected by CO$_2$ and the
decreasing extent of the climbing speed of explosion pressure is rather evident when the content of CH₄ is 10% and 12% respectively.

5) Fixing the content of CO₂ in the mixed gas and increasing the content of CH₄ from 5% in every group of experiments, we can find that the maximum climbing speed of the explosion pressure of the mixed gas of methane and air all increase firstly and then decrease. The change trend is in accordance with that without CO₂. Similarly, accordingly the maximum climbing speed of the explosion pressure of CH₄ and air mixed gas decrease with increasing the content of CO₂.

6) When there is CO₂ constantly pouring into the system from 0% to 10%, the maximum climbing speed of the explosion pressure of the mixed gas of methane and air reaches 39.7MPa/s when the content of CH₄ increases to 10%. At this moment, continuously pouring CO₂ into the system to 15% and 20% respectively, it can be found that the maximum climbing speed of the explosion pressure of the mixed gas of methane and air occurs when the content of methane is 8%. The decrease from 10% to 8% indicates that CO₂ has the function of explosion suppression.

| CO₂/0% | CO₂/5% | CO₂/10% | CO₂/15% | CO₂/20% |
|--------|--------|---------|---------|---------|
| 5%CH₄  | 0.31   |         |         |         |
| 6%CH₄  | 0.50   | 0.32    | 0.26    | 0.27    |
| 8%CH₄  | 0.61   | 0.42    | 0.32    |         |
| 10%CH₄ | 0.75   | 0.41    | 0.31    |         |
| 12%CH₄ | 0.52   | 0.33    |         |         |

Table 3. Experimental results of the maximum explosion pressure increase rate of the mixed gas of CH₄ and air

| CO₂/0% | CO₂/5% | CO₂/10% | CO₂/15% | CO₂/20% |
|--------|--------|---------|---------|---------|
| 5%CH₄  | 2.3    |         |         |         |
| 6%CH₄  | 10.9   | 8.7     | 6.5     | 5.4     |
| 8%CH₄  | 25.3   | 18.1    | 16.1    | 10.4    |
| 10%CH₄ | 39.7   | 25.2    | 19.1    |         |
| 12%CH₄ | 33.1   | 13.4    |         |         |

4. Numerical Simulation of the Explosion of the Combustible Gas in the Well

4.1. Numerical Simulation model
According to the design scheme of the underground drainage pipeline and the well system and the measurement in field, the partial three dimensional numerical model of the well is established with FLACS code. In the process of modeling, uniform grids are used in the whole calculation area.

The dimension of the calculation model is as Fig. 4. The diameters of the inspection well, cleaning well and drainage pipeline are 0.6m, 0.6m and 0.8m respectively. The diameter of the two air holes on the well lid is 0.03m, and the distances from their position to the edge of the well lid are both 0.1m. The depth of the well is 2.5m, and it extends to 2m left and 10m right from the bottom the well. The digestion tank with the cross-section of 4m×2m is set on the right side of the inspection well. On the top of the digestion tank is the cleaning well with 0.6m in diameter and 2 m in depth. The cleaning well is in the middle of the digestion tank top. The dirt deposit well with 0.8n in diameter is set on the left side of 2m away. Because this calculation model is the partial one of the well, the link gradient among the wells is not considered. Moreover, in order to reduce the calculation time, the length of each region is not established according to the actual measurement distance.

4.2. Simulation Cases
The simulation of gas explosion by pouring CO₂ into the mixed gas of methane and air is done. The content of CH₄ is 9.5%, and CO₂ is selected as the depressor. Six groups of simulation cases of CH₄
explosion simulation experiment with 0%, 6%, 9%, 12%, 15% and 18% CO2 are done. The simulation calculation shows that explosion all occurs in these six conditions.

![Model of the well system](image)

Figure 4: Model of the well system. 1—inspection well; 2—drainage pipeline; 3—dirt deposit well; 4—digestion tank; 5—cleaning well

4.3. Results

According to the recorded data by the pressure detector at the entrance of the well, the explosion pressure curves produced by these six groups of mixed gas with different content matching are shown in Fig.5. It can be seen that: (1) The content of the explosion outcome is only 26% when only methane explodes. With increasing CO2, the content of the explosion outcome increases. With the content of CO2 is 18%, the content of the explosion outcome increases to 46%. The proportion of CO2 is much in the outcome produced by the explosion of the mixed gas of methane and air. So pouring CO2 can effectively prevent the forward proceeding of the explosion and lead to the increase of the content of outcome. (2) CO2 has some effect on the temperature during the methane explosion. With increasing CO2, the temperature during the explosion decreases. The peak temperature decreases from 2260°C to 1700°C when the content of CO2 increases from 0 to 18%.

Then we study the effect of the initial pressure on the explosion pressure in the well with numerical simulation method. Assuming the other conditions are the same, the explosion process is studied only when the initial pressure increases from one standard atmospheric pressure to five standard atmospheric pressures. The calculation pressure and velocity of every measurement points are show in Fig.6. It can be seen that the maximum explosion pressure increases linearly with the increase in the initial pressure which indicates that the initial pressure has much effect on the maximum explosive pressure of the mixed gas.

![Effect of CO2 on the maximum explosive pressure of the mixed gas of CH4 and air](image)

Figure 5: Effect of CO2 on the maximum explosive pressure of the mixed gas of CH4 and air
5. Conclusions
(1) From the detection of the gas in the city well, it can be known that the main harmful gas is CH₄, CO₂ and a small amount H₂S.
(2) CO₂ has some effect on the methane explosion limit. It has a certain ability to suppress explosion, and with the increase of CO₂ content in the mixed gas, the explosion pressure decreases.
(3) CO₂ has the suppression action on the methane explosion. The delay time of the methane explosion ignition is longer, the effect on the flame temperature is larger. The effect of the explosion initial pressure is in almost linear relationship with the maximum explosion pressure.

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