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Experimental Research on the Influence of Ambient Humidity on Gas Explosion Characteristics

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Abstract:

To investigate the effect of environmental humidity on gas explosion characteristics, a series of tests were conducted using a 20 L spherical explosion simulation system. First, five key parameters—ignition energy, presence of combustible gases, environmental pressure, temperature, and coal dust—were analyzed. The results showed that the explosion limits of methane generally increase with ignition energy, but the decreasing trend of the lower limit and the increasing trend of the upper limit become flat as ignition energy continues to rise. Under high ignition energy, the lower explosion limit of methane drops to 1% when 1.5% H_2 (volume concentration) is added, and to approximately 2% with about 0.25% isobutane or n-hexane. Higher pressure reduces the lower limit and raises the upper limit, widening the explosion range, with a more pronounced effect on the upper limit. Elevated temperature exhibits similar effects. Below the explosion limit of coal dust, increasing coal dust concentration broadens the gas explosion limits.

The study then focused on the effects of humidity (15%–85% RH) on gas explosion limits, maximum explosion pressure, pressure rise rate, and ignition delay time. Results show that as humidity increases, both upper and lower explosion limits rise moderately. The maximum explosion pressure decreases (by 14.44% when humidity increases from 21.3% RH to 89.1% RH), and the time to reach it lengthens. The pressure rise rate decreases linearly, and the ignition delay time extends significantly (from 194 ms at 21.3% RH to 319 ms at 89.1% RH). Overall, increasing environmental humidity inhibits gas explosions to a certain extent.

AUTHOR KEYWORDS: gas explosion; environmental humidity; explosion characteristics

0 Introduction

China's energy structure is characterized by "abundant coal, limited oil, and scarce gas," which has resulted in coal accounting for over 50% of the country's primary energy consumption for many years[1-2]. At present, underground mining is the primary method for coal resource exploitation in China. However, gas explosions remain one of the major hazards in underground coal mining, posing serious threats to miners' lives, hindering safe production, damaging surrounding ecological environments, and exerting negative social impacts [3-5]. According to incomplete statistics, between 2013 and 2023, China recorded 65 major coal mine accidents with 1,013 fatalities, and 4 extraordinarily severe accidents with 154 fatalities. Among these, gas-related accidents accounted for 51% of the total[6]. Therefore, it is

imperative to identify the key factors influencing gas explosions, reduce the occurrence of such accidents, and minimize their impacts within acceptable limits.

Gas explosion is a complex and violent oxidation reaction: when gas (primarily composed of methane) mixes with air to form a combustible mixture, and the concentration falls within the explosive limits, the presence of a sufficiently energetic ignition source can trigger an explosion. Key factors influencing gas explosion include gas concentration, ignition energy, ambient temperature, ambient pressure, and humidity: Gas concentration directly determines combustibility (the explosive limits of methane in air are typically 5%–15%, and concentrations that are too high or too low cannot trigger an explosion); the ignition source must exceed a threshold energy (higher energy makes ignition easier and may enhance explosion intensity); elevated ambient temperature accelerates molecular motion, facilitating reactions and broadening the explosive range; changes in ambient pressure affect intermolecular spacing and reactivity, with increased pressure altering the explosive limits accordingly.

Extensive domestic and international research has been conducted on gas explosion limits and parameters under varying environmental conditions. Examples include: establishing multi-component gas explosion systems to investigate the effects of hydrogen, isobutane, and n-hexane on the lower explosion limit of methane[7]; examining the effect of coal dust on methane explosion limits [8-10]; studying the influence of methane concentration, ignition energy, and initial pressure using self-developed systems and apparatus; testing methane explosion limits and minimum ignition energies in 20 L vessels to quantify their relationship with pressure and temperature; investigating the effect of ambient temperature on methane explosion limits[11]; exploring ignition energy effects using high-speed photography and data acquisition[12]; employing nitrogen dilution to predict maximum safe oxygen concentrations[13]; calculating and plotting critical oxygen limits for coal gas[14]; experimentally determining minimum oxygen concentrations for artificial coal gas and liquefied petroleum gas[15]; and analyzing the effects of oxygen concentration limits on mine gases[16-17].

1 Analysis of the Main Influencing Factors of Gas Explosion Characteristics

The attainment of explosive limits in gas concentration is one of the fundamental prerequisites for a gas explosion. The commonly cited range of *5%–16%* for methane explosion limits refers to methane–air mixtures under normal temperature, atmospheric pressure, and low-energy ignition conditions. In reality, gas explosion limits are not fixed values; they are influenced by a variety of factors. Extensive experimental studies have demonstrated that ignition energy, admixture of other combustible gases, ambient pressure, ambient temperature, and the presence of coal dust all affect the explosion limits of methane to varying degrees.

1.1 Influence of Ignition Energy on Explosion Limits

Ignition sources <1 J are weak, while >10 J are strong. Most methane explosion experiments use weak ignition, with its lower explosion limit (LEL) around 5%. High-energy ignition experiments showed it significantly affects methane's explosion limit, lowering LEL to 3.65%. Tests under different ignition energies revealed methane's explosion limits generally rise with energy, but further energy increase flattens the lower limit's downward and upper limit's upward trends (Fig. 1).

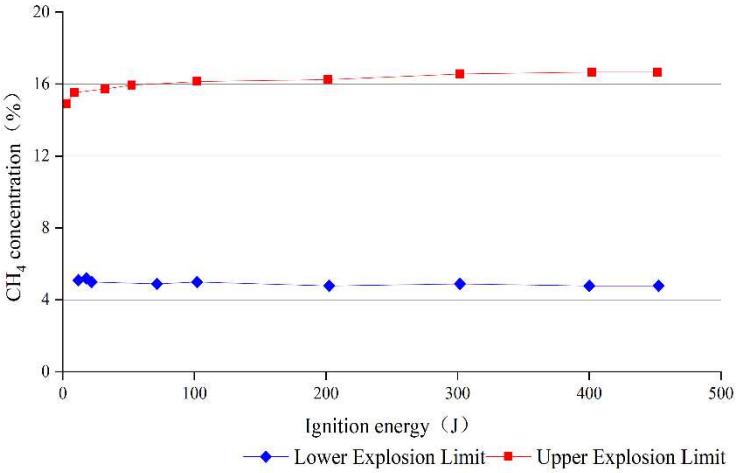


Fig. 1Gas explosion limit under different ignition energy

1.2 Influence of Admixed Combustible Gases on Explosion Limits

Extensive experimental evidence shows that admixture of other combustible gases (e.g., hydrogen, ethane) significantly alters methane's explosion limits. Using a multi-component gas explosion system, the lower explosion limits (LELs) of methane mixed with hydrogen, isobutane, and n-hexane were determined. Results reveal higher concentrations of these additives lower methane's LEL, with reduction extent dependent on the admixed gas type and concentration (Fig. 2). Under strong ignition, methane's LEL drops to 1% when hydrogen reaches 1.5% by volume, and to ~2% when isobutane or n-hexane is ~0.25%.

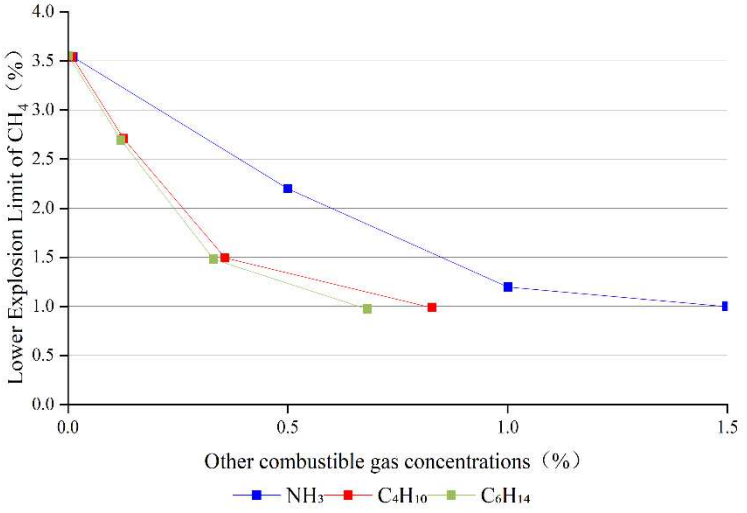


Fig. 2Lower gas explosion limit mixed with other combustible gas

1.3 Influence of Ambient Pressure on Explosion Limits

As ambient pressure increases, intermolecular distance shrinks, gas density rises, and molecular collision probability increases. This makes more molecules participate in initial reactions, accelerates

reaction rates, and widens explosion limits by boosting explosion likelihood.

Custom-built system experiments showed rising ambient pressure reduces methane's lower explosion limit, raises its upper limit, and expands the explosion range. Notably, pressure impacts the upper limit more than the lower one (Fig. 3). Similar results were found in studies on methane explosions at low (0.1–0.2 MPa) and high (1–12.5 MPa) pressures (Fig. 4).

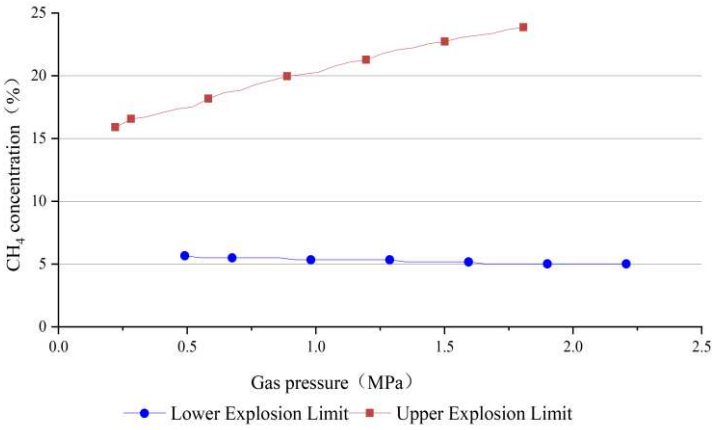
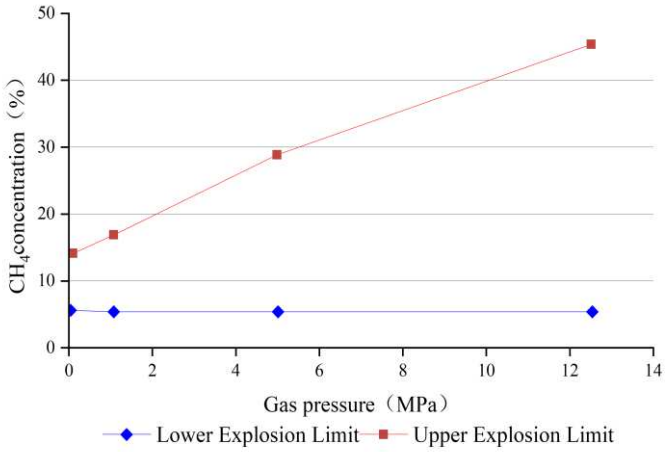
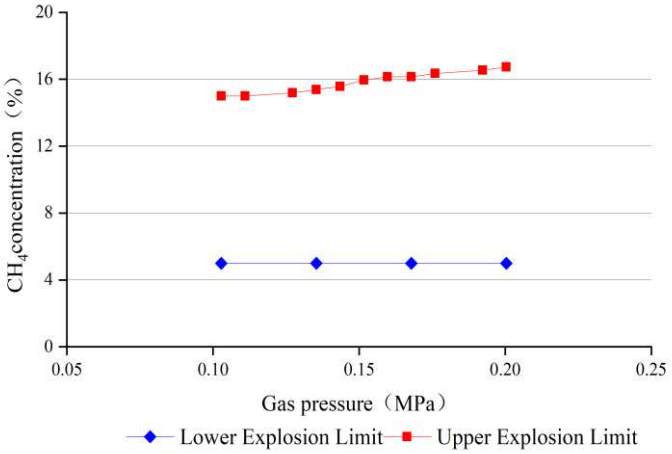


Fig. 3 Change of gas explosion limits under different enviormental pressure



（a）Methane explosion limits under relatively low ambient pressure conditions



（b）Methane explosion limits under relatively high ambient pressure conditions

Fig. 4 Change of gas explosion limits under lower and higher enviormental pressure

1.4 Influence of Ambient Temperature on Explosion Limits

As ambient temperature increases, molecular internal energy rises, molecular motion accelerates, and collision frequency increases. This enhances the production of free radicals and facilitates the initiation of combustion reactions. Additionally, elevated temperature accelerates chemical reaction rates, sustaining chain reactions. Therefore, increasing ambient temperature widens methane explosion limits.

Experimental investigations under varying temperature conditions, designed to simulate fire scenarios, confirmed that temperature significantly affects methane explosion limits. Results showed that as temperature increased, the LEL decreased, the upper explosion limit increased, and the overall explosion range expanded (Figs. 5 and 6).

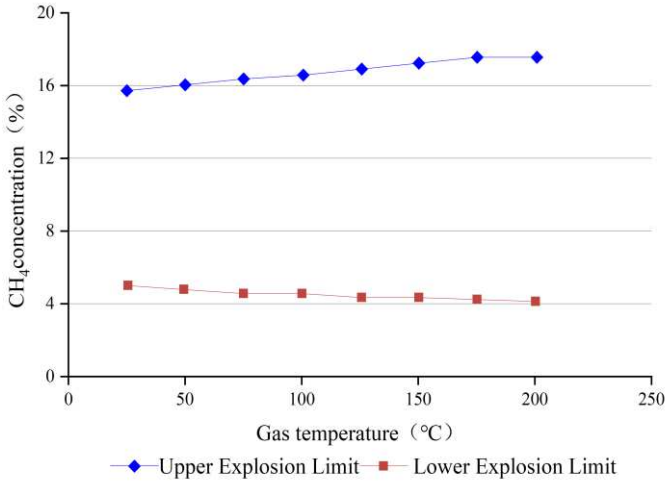


Fig. 5 Change of gas explosion limits under different enviormental temperture(10J ignition energy, 0.1 Mpa environmental pressure)

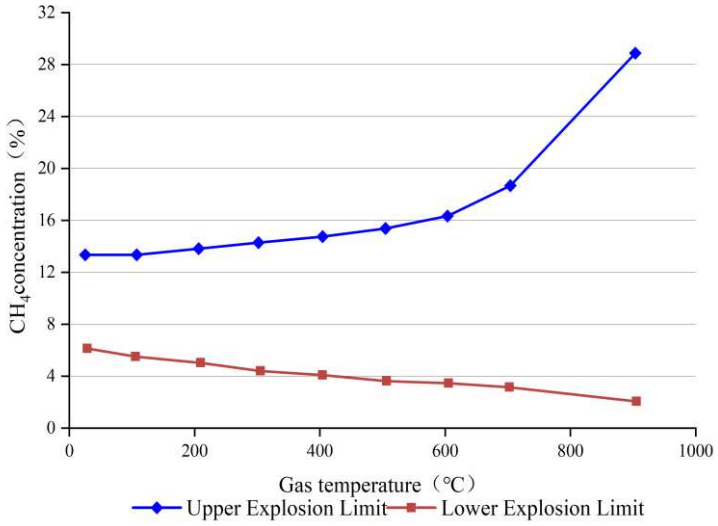


Fig. 6 Change of gas explosion limits under diffierent environmentl temperture

1.5 Influence of Coal Dust on Explosion Limits

Heated coal dust volatilizes combustible gases, adding fuel near the ignition source to facilitate methane explosions. An explosive coal dust cloud in methane alters methane's explosion limits, usually lowering the LEL.Experiments with different coal dust concentrations showed that below coal dust's explosion limit, higher coal dust concentrations widened methane's explosion limits (Fig. 7). Experiments with coal dust from different mining areas had consistent trends but varying influence magnitudes due to dust properties (Fig. 8).

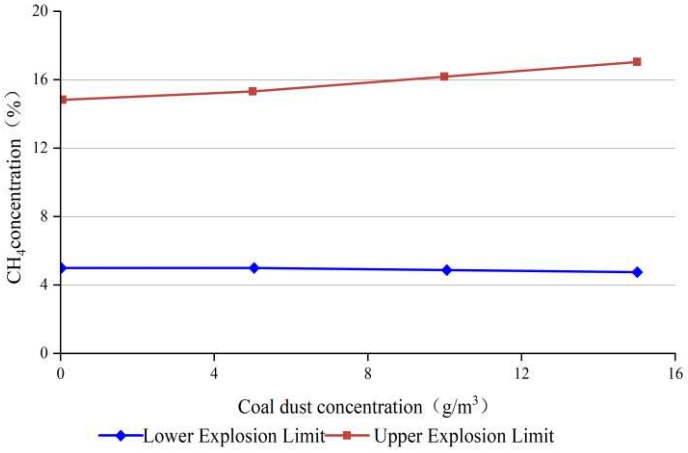


Fig. 7 Gas explosion limits under different coal dust content(coal dust lower explosion limit 45g/m³)

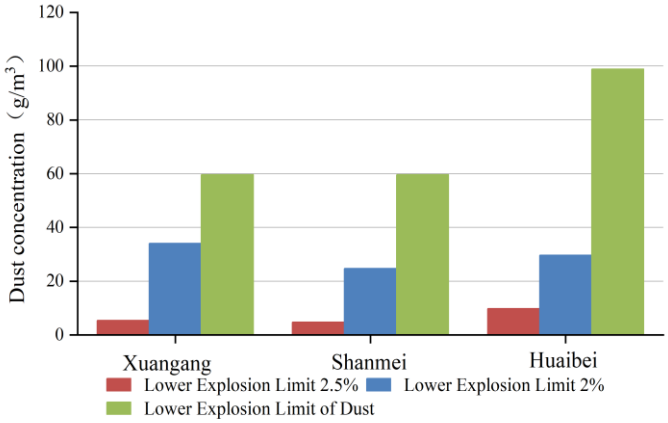


Fig. 8 Coal dust influence of coal gas explosion limits

1.6 Influence of Ambient Humidity on Gas Explosion Limits

Due to the limited analysis of environmental humidity at the current stage, we subsequently conducted a quantitative analysis of environmental humidity.

2 Experimental Conditions of Ambient Humidity

To date, few studies have examined ambient humidity's effect on gas explosion characteristics, with no systematic experiments in the literature. This paper thus designed explosion experiments under different humidities to analyze humidity's effects on these characteristics, filling a research gap and providing more references for explosion theory and safety control.

2.1 Experimental System

Underground coal mine environments are complex, making long-term, large-scale field tests challenging. Thus, researchers often use laboratory-scale experimental platforms based on similarity principles; repeatable, comparable experiments with comprehensive monitoring effectively examine humidity's impact on gas explosions. The gas explosion simulation device has three subsystems: gas distribution, explosion chamber, and data acquisition/analysis.

2.1.1 Gas Distribution System

The gas distribution system prepares explosive mixtures for methane explosion experiments (structure in Fig. 9). Two steel cylinders supply dry compressed methane and air, respectively; an air compressor provides humid lab air, a purifier removes impurities, pressure/flow regulators control gas parameters, and a mixing chamber ensures homogeneous mixtures before entering the explosion chamber.

During preparation, gases pass through regulators, purifiers, and stabilizing valves into the mixing chamber. Adjusting pressures/flow rates yields mixtures with specific compositions and humidity levels.

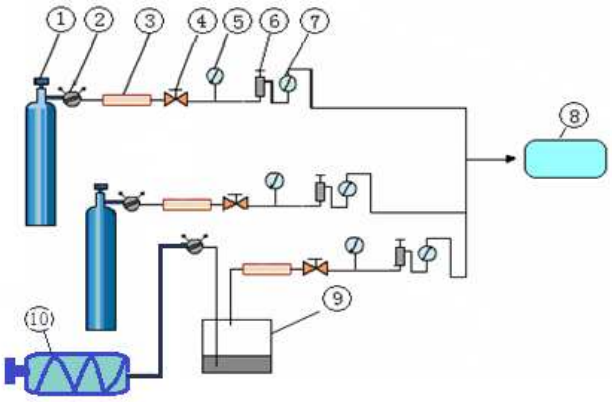


Fig. 9 Valve system schematic diagram

2.1.2 Explosion Chamber

The explosion chamber forms the core of the system (Fig. 10). A 20 L spherical chamber, widely adopted internationally, was used. It consists of a double-layer forged steel shell, with circulating thermostatic water in the interlayer to maintain chamber temperature (±1 °C). The cover and base are sealed with O-rings to ensure airtightness.

The ignition system employs electrode discharge. A copper rod passes through the chamber cover, connecting to a high-voltage power source externally and terminating with an adjustable sharp–sharp electrode pair at the chamber center. During experiments, a spark discharge between electrodes ignites the mixture.

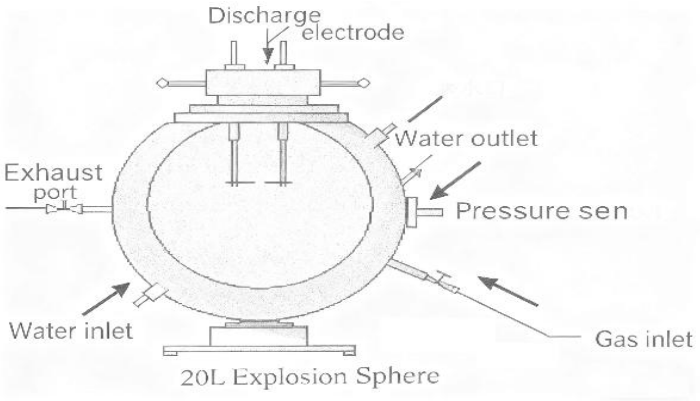


Fig. 10 Explosion cavity structure diagram

2.1.3 Data Acquisition and Analysis

The data acquisition system records, converts, and processes explosion signals. It consists of a piezoelectric pressure sensor (2000GAB1001A30A), a signal amplification circuit, and a Peripheral Component Interconnect-1710 (PCI-1710) acquisition card.

During explosions, the pressure signal on the chamber wall is collected by the sensor, amplified, converted to digital data, and plotted into pressure–time curves.

2.2 Experimental Procedure

2.2.1 General Plan

Explosion limits under different initial conditions were estimated from empirical and theoretical considerations. Experiments were conducted by gradually increasing or decreasing methane

concentrations in steps ≤0.01% until ignition either just occurred or failed to occur. The corresponding concentration was then taken as the explosion limit under the given humidity.

The experimental flow is illustrated in Fig. 11.

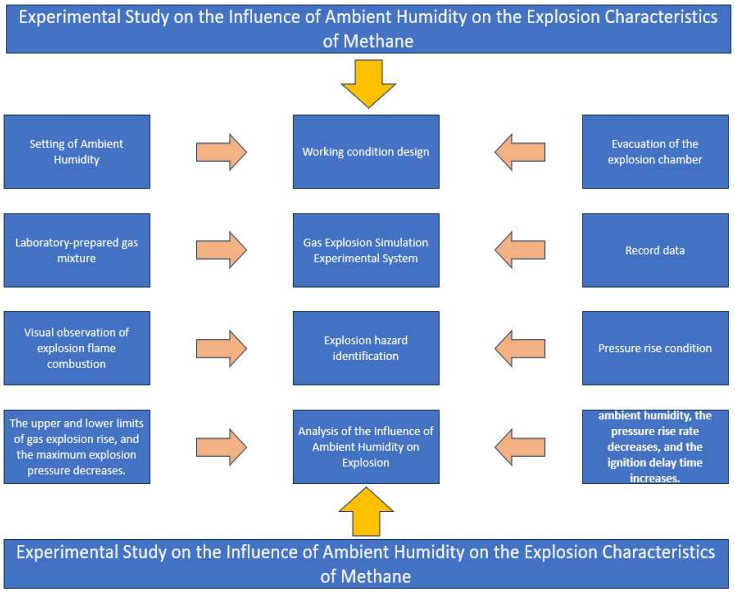


Fig. 11 Experimental structure diagram

2.2.2 Experimental Steps

The experimental procedure comprised two steps: gas preparation and explosion testing. Gas preparation was performed manually, while ignition and data recording were automated.

①Gas Preparation

Source gases included high-purity compressed methane (>99%, humidity <10%), dry compressed air (humidity <10%), and laboratory air with adjustable humidity (via humidifiers or dehumidifiers). Gases were precisely controlled by regulators and mixed in a 10 L chamber, with composition error ≤±0.01%.

Humidity ranges were prepared as follows:

15%–25% RH: dry methane + dry compressed air

40%–52% RH: dry methane + dehumidified laboratory air

62%–70% RH: dry methane + natural laboratory air (≈70% RH)

77%–90% RH: dry methane + humidified laboratory air (>90% RH)

During the gas distribution process, dry air or laboratory air is first introduced into the mixing chamber using a high-pressure cylinder or an air compressor. Subsequently, based on the chamber volume and the target concentration of the premixed gas, the required volume of methane is calculated. Dry methane is then injected into the mixing chamber through flow regulation to complete the preparation of the mixture. After mixing, the methane concentration within the chamber is measured multiple times to ensure the homogeneity of the combustible mixture.

②Explosion Testing

Before each test, the chamber was evacuated to remove residual gases. The prepared mixture was then introduced, and ignition triggered. Data acquisition began simultaneously.

2.2.3 Explosion Identification

Explosion identification, namely distinguishing between explosive and non-explosive outcomes, is

one of the key tasks in this experiment. It involves two aspects: (i) determining whether an explosion occurs after ignition of the gas mixture, and (ii) assessing whether the mixture possesses explosion hazard.

For determining whether an explosion has occurred, reference was made to ASTM E681 (American Society for Testing and Materials) and DIN 251469 (Deutsches Institut für Normung). By comparing the visual observation of flame combustion with the measured pressure rise, a pressure increase of 7% or greater was adopted as the criterion for explosion occurrence.

For determining whether the gas mixture exhibits explosion hazard, the following criterion was established with reference to previous studies: if an explosion occurs in any of ten ignition trials, the mixture is considered explosive; if no explosion occurs in ten consecutive trials, the mixture is regarded as outside the explosive limits and thus non-hazardous.

3 Conclusions

3.1 Effect of Ambient Humidity on Explosion Limits

Using an ignition energy of 10 J, under normal temperature and standard atmospheric pressure, experimental determination of methane gas explosion limits under different ambient humidity conditions (with ambient humidity ranging from 15% to 85%) was carried out. The measured upper and lower explosion limit results are shown in Tables 1 and 2.

Analysis of experimental results shows ambient humidity exerts a certain influence on gas explosion limits. It has the same effect on methane's upper and lower explosion limits: both rise gradually with increasing humidity. Specifically, when humidity increases from 20% RH to 86.1%, the lower limit rises from 4.93% to 5.26% (a 6.7% increase); when humidity goes from 18% RH to 85.9%, the upper limit increases from 14.9% to 15.4% (a 3.4% increase) (see Fig. 12). The reason is that increased humidity makes moisture dilute explosive gas and absorb ambient heat, reducing methane's combustion rate—thus requiring a higher gas concentration to sustain the reaction.

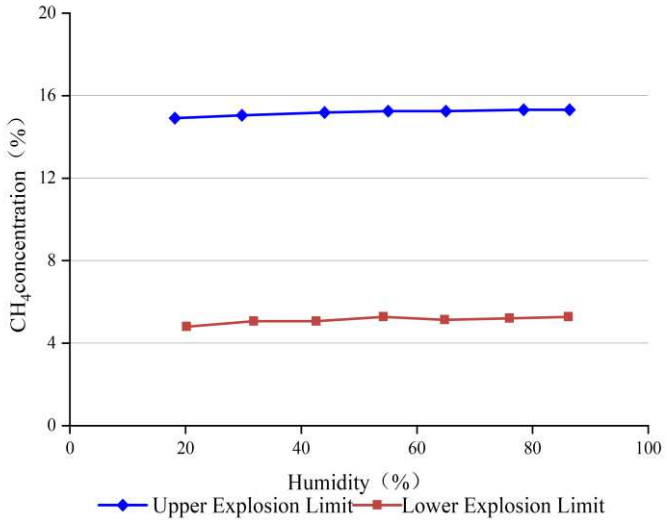


Fig. 12 Change of gas explosion limits under different environmental humidity

3.2 Influence of Ambient Humidity on the Maximum Explosion Pressure of Methane

Piezoresistive pressure sensors were used to detect the constant-volume explosion pressure inside the vessel. With ignition at the center of the explosion vessel, wall cooling and gas leakage (causing heat loss) only occur when the flame reaches the vessel wall; thus, the pressure measured by sensors on the vessel wall is close to the maximum constant-volume explosion pressure. Experimental data were used to analyze the variation of explosion pressure with ambient humidity.

A typical pressure–time curve under natural laboratory humidity conditions is shown in Fig. 13.

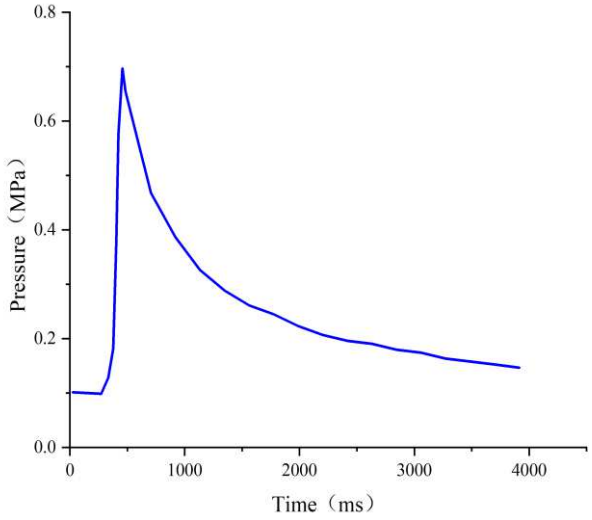


Fig. 13 Coal gas explosion pressure curve under 35%RH environmental humidity

A 200ms ignition delay was artificially set for gas detonation to ensure more uniform gas mixing in the vessel and system stability. As shown in Fig. 13, after ignition, the time-dependent variation of gas explosion pressure can be divided into three stages:Slow oxidation stage: After ignition (post-200ms), pressure does not rise immediately but undergoes a tens-of-millisecond reaction induction period (ignition delay time); Fast reaction stage: Pressure then rises rapidly, taking ~165ms from the start of rise to maximum explosion pressure; Reaction extinction stage: After reaching maximum pressure, internal pressure decreases gradually. Since the system is not under ideal constant-volume adiabatic conditions, pressure drops but retains a certain overpressure after ~400ms of data collection, and continues to decrease until approaching standard atmospheric pressure.

Under natural laboratory humidity, explosion pressure starts to rise gradually ~70ms after ignition. Pressure rise rate accelerates significantly as the reaction proceeds; per the Arrhenius empirical formula, combustion reaction rate correlates closely with temperature—temperature increases during explosion, boosting chemical reaction rate and thus accelerating pressure rise. Under this condition, the maximum explosion pressure is 7.036atm (absolute pressure), reached ~235ms after ignition, followed by a gradual drop.

The variation of gas explosion pressure with time was analyzed under ambient humidities of 21.3%RH, 35.7%RH, 59.7%RH, and 89.1%RH (gas concentration: 12.5%), as shown in Fig. 14.

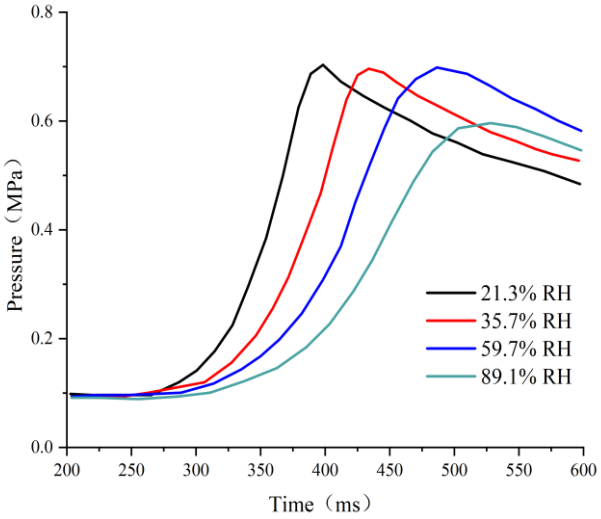


Fig. 14 Contrast pressure curve of coal gas explosion under different environmental humidity

Analysis of Fig. 14 shows that under different ambient humidities, the time-dependent gas explosion pressure curves all conform to the typical explosion pressure variation law of closed vessels. With increasing ambient humidity, the maximum explosion pressure decreases gradually—dropping by 14.44% when humidity rises from 21.3%RH to 89.1%RH, indicating a significant influence of ambient humidity on gas explosion pressure.

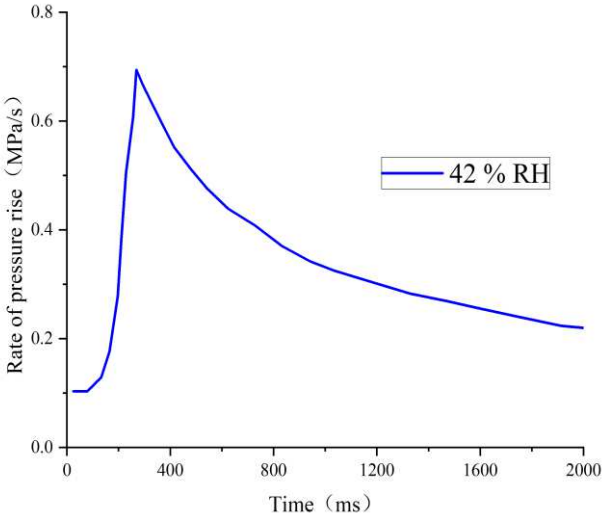
Meanwhile, the time to reach maximum explosion pressure varies with humidity: it occurs at 0.394s, 0.434s, 0.493s, and 0.519s as humidity increases from 21.3%RH to 89.1%RH, showing a clear prolongation of reaction time.

Per Arrhenius theory, chemical reactions rely on molecular collisions. Increased humidity dilutes and cools the gas mixture, reducing molecular internal energy and the probability of effective molecular collisions—thus decreasing the maximum gas explosion pressure and prolonging the time to reach it.

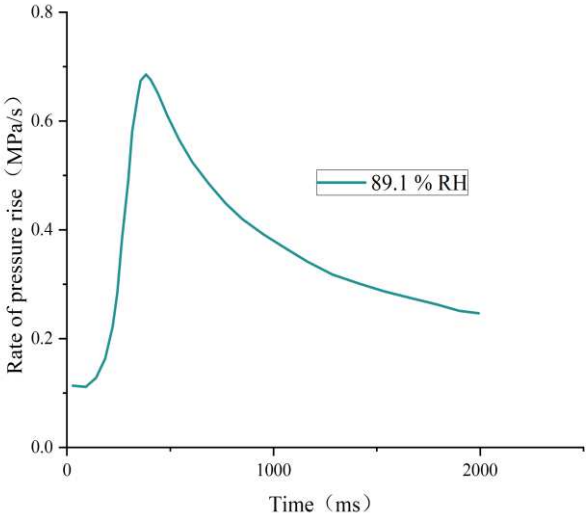
3.3 Influence of Ambient Humidity on the Pressure Rise Rate of Methane Explosions

Methane's maximum pressure rise rate is a key parameter for evaluating explosion characteristics. In this section, laboratory experiments were conducted using a 20 L explosion test system under controlled environmental conditions to investigate how this rate varies with ambient humidity, and the experimental data were analyzed to clarify their relationship.

12.5% concentration methane was selected as the test subject, and its explosion pressure rise rates were measured under different humidity conditions. When the relative humidity was 42.8% RH and 89.1% RH, the corresponding pressure rise rate curves were obtained (Fig. 15), where the slope of the red line represents the maximum pressure rise rate. Following the same method, the maximum pressure rise rates of 12.5% methane under other humidity conditions were also measured, with results summarized in Table 3.



（a）42.8%RH



（b）89.1%RH

Fig. 15 Rising rate of coal gas explosion maximum pressure under different environmental humidity

The table shows methane's maximum explosion pressure rise rate decreases slightly with increasing ambient humidity. Data fitting (Fig. 16) of measured values across experimental humidities shows they roughly align on a straight line, with a linear decrease as humidity rises: at 89.1% RH, the rate drops from 6.155 MPa/s (21.3% RH) to 5.354 MPa/s.

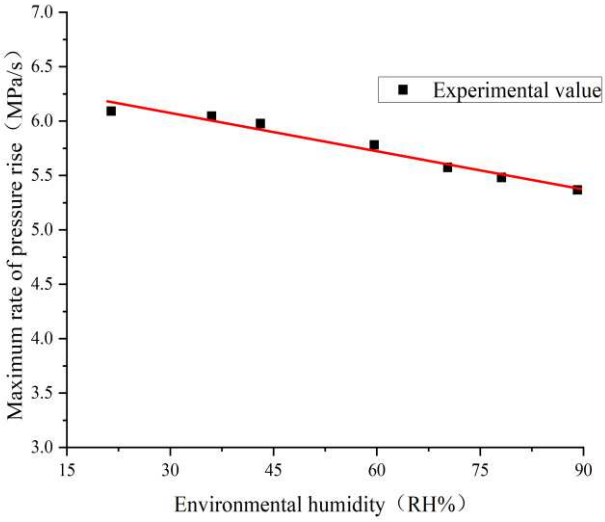


Fig. 16 Change curve of maximum pressure rising rate with environmental humidity

As ambient humidity increases, water vapor dilutes and cools the methane-air mixture, lowering temperature and reducing methane's explosion reaction rate—thus decreasing the maximum pressure rise rate.

3.4 Influence of Ambient Humidity on the Ignition Delay Time of Methane Explosions

During the slow oxidation stage of gas explosions, a gas-air mixture does not immediately undergo an explosive reaction or pressure rise when in contact with an ignition source; instead, it requires a short interval to initiate the reaction—a phenomenon called ignition delay, with the interval duration defined as ignition delay time. For combustible mixtures at specific temperatures and pressures, ignition triggers rapid temperature rise, enhanced light emission, and accelerated chemical reactions, yet quantitative characterization of these features remains challenging.

Combustible gases have multiple definitions of ignition delay time, leading to varying experimental results. For instance, it can be defined by pressure rise onset or a specific component's sudden concentration increase; N. Lamoureux et al. defined it via the calculated relationships of alkane, oxygen concentrations and temperature. Due to experimental constraints, this study defines it as the time between ignition triggering and a pressure sensor detecting initial pressure rise.

Gas explosion ignition delay time relates to gas concentration: the closer to the stoichiometric mixture, the more complete the reaction and the shorter the delay. Its detection underpins explosion isolation/suppression studies. This study, under 12.5% gas concentration, ambient temperature/pressure, and 10 J ignition energy, explored delay variation with humidity; these data offer effective theoretical support for such studies.

The variation of ignition delay time for a gas concentration of 12.5% and an ignition energy of 10 J under different environmental humidities is presented in Table 4.

The experimental data presented in Table 4 were plotted as a curve, as shown in Fig 17. It can be observed that the ignition delay time of gas explosions gradually increases with increasing environmental humidity. When the relative humidity is 21.3% RH, the ignition delay time for a gas concentration of 12.5% is 194 ms, whereas at 89.1% RH, the ignition delay time increases to 319 ms for the same gas

concentration.

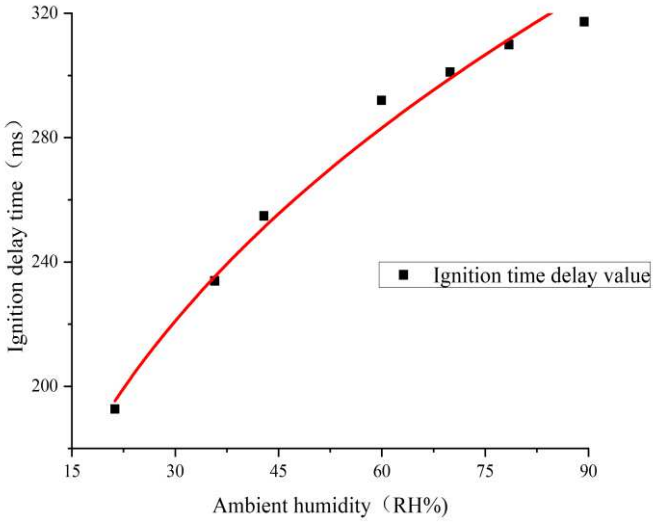


Fig. 17 The change curve of ignition delay time with environmental humidity

Based on the above summary analysis of factors influencing gas explosions and the experimental results, it can be concluded that an increase in environmental humidity exerts a certain inhibitory effect on gas explosions.

3.5 Engineering Applications

3.5.1 Preliminary On-Site Application of the Early Warning System

To assess the practical value of humidity's gas explosion inhibition, this study integrated humidity into a coal mine gas explosion early warning system and did preliminary on-site trials. The experiments were conducted at Luling Mine (Huaibei, Anhui) and Sihe Mine (Jincheng, Shanxi), focusing on verifying humidity's actual effectiveness in the system(Fig.18).

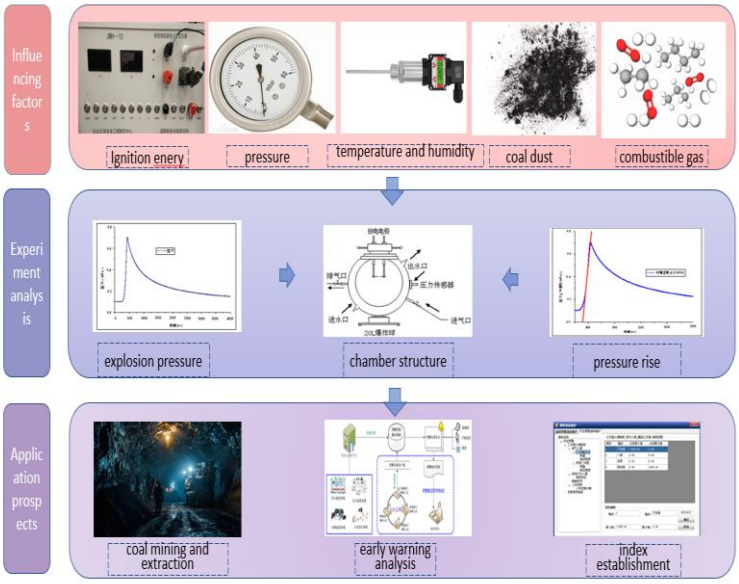


Fig. 18Application prospects

3.5.2 Overview of the Luling Mine Experiment

Luling Coal Mine, a high-gas mine with gas incidents, tested an early warning system. It had humidity sensors for real-time working face monitoring and issued integrated warnings using gas concentration, temperature and other data.

During the test, the system found higher humidity delayed gas explosion risks. For example, when a working face's humidity rose from 35% to 70%, though gas exceeded limits temporarily, it didn't issue an immediate high-level alarm; instead, it assessed risks with humidity considered, proving humidity's explosion-inhibiting effect.

3.5.3 Overview of the Sihe Mine Experiment

The Sihe Coal Mine's East Shaft area is a high-gas mine. During the trial, the focus was on evaluating the weighting of the humidity parameter within the early warning model. The system dynamically adjusted the warning thresholds by collecting humidity data in real time, which significantly improved the accuracy and reliability of the warnings.

The results indicate that the incorporation of the humidity parameter enabled the early warning system to more accurately reflect the actual risk under high-temperature and high-humidity conditions. This approach effectively prevented false alarms caused by exceeding gas concentration limits alone, thereby enhancing the system's practicality and user acceptance.

3.5.4 Integration of the Humidity Parameter into the Early Warning System

In this study, humidity was incorporated as an independent environmental parameter within the gas explosion early warning indicator system. Data were collected in real time via humidity sensors deployed underground and transmitted to the central warning platform. The platform dynamically adjusted parameters such as the upper and lower limits of gas explosion, maximum explosion pressure, pressure rise rate, and ignition delay time based on the humidity values, thereby enabling more accurate risk assessment.

3.5.5 Analysis of Application Effectiveness

The on-site trials conducted in the two mine areas confirmed the feasibility and effectiveness of incorporating environmental humidity as a parameter in the gas explosion early warning system. Elevated humidity was found to exert a certain inhibitory effect on gas explosions, and this conclusion was further validated in practical application. By integrating the humidity parameter, the early warning system significantly improved both the accuracy and timeliness of warnings, providing a new technical approach for gas hazard prevention and control in coal mines.

4 Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

5 Statements and Declarations

5.1 Conflict of interest statement

All authors disclosed no relevant relationships.

5.2 Funding sources

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6 Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Xianglan LIU, Fuchao Tian, Zewen Wang.

The first draft of the manuscript was written by Xianglan LIU, and all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

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