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Research on Active CO2 Fire Extinguishing Technology for Initial Annular Pool Fires in Storage Tanks

Yong Huang

huangyong001@cczu.edu.cn

Changzhou University

Shiyu Zhu

Changzhou University

Axiang Tao

Changzhou University

Deyu Xu

Changzhou University

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Research on Active CO2 Fire Extinguishing Technology for Initial Annular Pool Fires in Storage Tanks

Abstract

To improve the efficiency of extinguishing initial fires in the annular gaps of storage tanks, this study designs an automatic trigger carbon dioxide active fire extinguishing system. The core innovation of the system lies in the use of molten material (EVA hot-melt adhesive) to seal the spray holes, which melt upon heating during the early stage of a fire and automatically release high-pressure carbon dioxide, responding quickly. Two key engineering parameters, namely the layout of the spray holes and the installation height, were experimentally studied for their impact on fire suppression performance. The experiment found that reducing the spray height from 30cm to 20cm could significantly shorten the time to extinguish the flame, with the optimal condition (8 holes, 20cm high) taking only 15 seconds. At the same time, increasing the number of spray holes from 4 to 8 can further reduce the fire extinguishing time by 14.3% to 25%, because the porous arrangement forms a more uniform inert gas cover. Both simulations and experiments have confirmed that low-position, porous jetting enables the carbon dioxide jet to penetrate the flame plume more effectively and act directly on the combustion reaction zone, thereby maximizing its cooling and suffocation effects. This study provides direct guidance on parameter optimization for tank safety design and demonstrates the feasibility and efficiency of an active fire extinguishing device for initial annular pool fires.

Keywords Active fire extinguishing, Carbon dioxide, Initial fires, Tank fire

1 Introduction

With the increasing demand for the storage and transportation of raw materials and products in the chemical industry, the application of large storage tanks is becoming more widespread. The tanks contain flammable, explosive, and volatile hazardous chemicals. To reduce evaporation loss, they are often equipped with floating plate structures. However, the annular gap between the float and the tank wall is prone to accumulating volatile flammable vapors, which may cause fires or even explosions when exposed to ignition sources such as lightning, static electricity, or high temperatures, posing a serious threat to the integrity of the tank and storage safety [1-4]. Therefore, there is an urgent practical need to develop efficient, clean technologies for the active suppression of tank fires.

Tank pool fires typically go through the stages of initial, development, and full development. In the early stage of a fire, the flames are usually confined to a local area, and the heat radiation is low, which is a critical window for intervention to prevent the spread of the disaster and to reduce disposal costs [5-6]. If not effectively controlled, the fire will rapidly develop into a full-surface pool fire that covers the entire liquid

surface, which is extremely difficult to extinguish and may cause secondary disasters such as boiling over [7]. For initial fires formed in annular crevices, a full liquid surface fire can be avoided if appropriate firefighting methods are used during the annular fire stage. Therefore, the development of rapid, automatic active fire-extinguishing technology for initial pool fires in storage tanks is of great significance for improving process safety.

Research on extinguishing technologies for tank pool fires has attracted the attention of relevant scholars. Fine water mist fire suppression technology offers of fast fire suppression speed and low water consumption [8-11]; Foam extinguishing technology offers of high efficiency and strong ability to suppress reignition [12-16]. Fine water mist extinguishing technology, however, is prone to causing boiling over in high-temperature oil fires; Foam extinguishing techniques produce toxic by-products and are prone to bursting at high temperatures. In addition, traditional fire protection systems are mostly passive and have lagging response times, making it difficult to control fires in their early stages effectively. In contrast, inert gas fire-extinguishing technology has clear advantages for early-stage tank fire suppression [17-18]. It is energy-efficient, leaves very little residue, has high thermal stability, and is usually harmless to equipment. Torikai[19] proposed using rubber balloons filled with inert gas to extinguish pool fires. Wang et al. [20] found through experiments and simulations that nitrogen has a significant asphyxiating effect on ethanol, diesel, and gasoline pool fires in confined Spaces. Zhang et al. [21] studied the effects of liquid nitrogen flow rate and pipe diameter on fire extinguishing efficiency. They found that fire extinguishing efficiency was positively correlated with the nitrogen injection flow rate injected into the pipe gallery. Hwan et al. [22] investigated the effects of the discharge area and the type of atomized gas on the fire-extinguishing performance of a heptane tank using a two-fluid atomizer. Bai et al. [23] investigated the fire-extinguishing performance of liquid CO_2 in high-alcohol spirits pool fires and demonstrated the advantages of liquid CO_2 in large-scale high-temperature fire cooling and explosion suppression. However, most current studies have focused on full-liquid surface fires, and there is insufficient research on extinguishing techniques for initial fires in annular gaps of storage tanks.

To address these research gaps, this study designs and develops a carbon dioxide active fire extinguishing device based on the melting trigger mechanism, aiming to achieve rapid automatic suppression of initial fires in tank annular gaps. By conducting experiments to extinguish fires in anhydrous ethanol pools, the effects of different numbers of nozzles and spray heights on the evolution of fire suppression time, the temperature field, and the oxygen concentration field were systematically studied. The flow field diffusion characteristics and inerting process of the carbon dioxide jet were analyzed using computational fluid dynamics (CFD) simulations. This study aims to

clarify the law of the influence of key parameters on fire extinguishing efficiency, reveal the dominant fire extinguishing mechanism of the combined effect of cooling and asphyxiation, and provide experimental evidence and theoretical reference for the active safety protection technology of initial fires in storage tanks.

2. Experimental setup and methods

2.1 Experimental Setup

The experimental system, as shown in Figure 1, comprises stainless steel storage tanks, floating discs, circular pipes, carbon dioxide cylinders, and data acquisition systems.

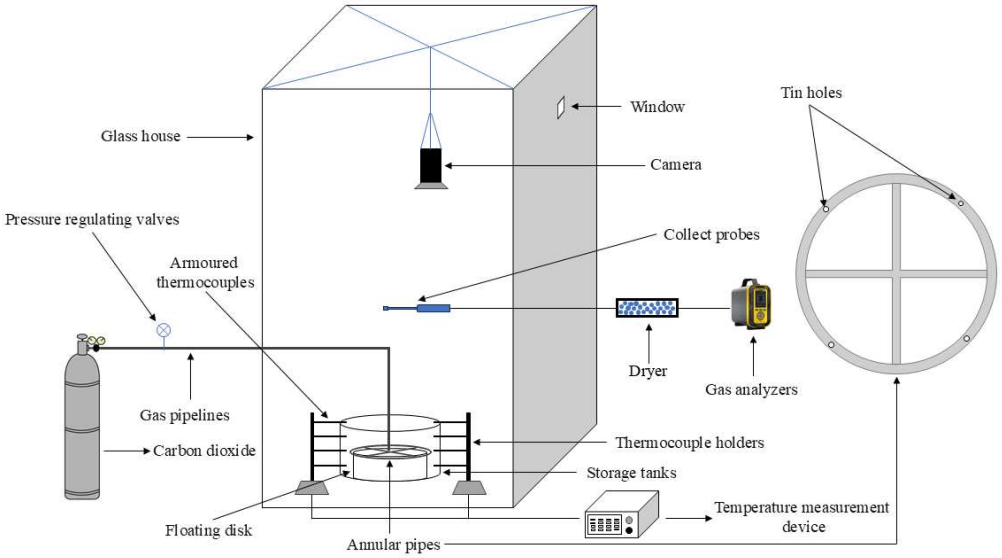


Fig.1 Schematic diagram of the experimental setup

The glass room is 1.2m×1.2m×2m and the window size is 20cm×20cm. The experimental setup was mainly a stainless steel simulated storage tank with an inner diameter of 590mm and a height of 350mm. Inside the tank was placed a hollow cylindrical, stainless-steel disc with an inner diameter of 500mm and a height of 200mm, and the upper surface was equivalent to the floating disc of the storage tank. A circular pipe with an inner diameter of 540mm and an inner diameter of 20mm was fixed above the float. Circular spray holes with a diameter of 4.0mm were arranged at equal intervals along the circumferential direction at the bottom of the circular pipe, and the spray holes were sealed with molten material. The molten material used is EVA hot-melt adhesive, which has a melting point of 80 °C. The circular pipe is connected to the high-purity carbon dioxide gas cylinder via a hose, and the cylinder is pressurized 0.3MPa. The data acquisition system includes cameras, temperature acquisition devices, and gas analyzers. The temperature acquisition equipment includes K-type

thermocouples and paperless recorders. The K-type thermocouple, model WRNK-191, has a temperature measurement range of 0 to 1100 °C; The paperless recorder model is the Huipu TCP-500XL-1116, with 16 channels and a temperature collection range of -200 to 2320 °C. The gas analyzer is a Keyence JESMS400G, with a sampling accuracy of approximately ±3%, an oxygen concentration collection range of 0 to 30%Vol, and a collection frequency of 5 seconds per time.

2.2 Experimental Methods

Before the experiment, the data acquisition system and the active fire extinguishing device were properly arranged in the glass room. Among them, K-type thermocouples are symmetrically arranged on both sides of the tank perpendicularly through brackets (thermocouple perforations enter the tank interior), each thermocouple is vertically spaced 10cm apart and located at the perpendicular bisector of the line connecting the centers of adjacent perforations, the lowest thermocouple is 10cm away from the bottom of the tank, and there are four thermocouples on each side to capture the temperature values at different positions within the tank. The collection probe of the gas analyzer is placed 60cm directly above the center of the tank's bottom surface to monitor changes in oxygen concentration. The experiment was recorded by a ceiling-mounted camera.

Each time, 300mL of 99.7% anhydrous ethanol was measured and poured into the experiment tank. After ignition, the melting holes at the bottom of the circular pipe are heated and melt, expelling carbon dioxide until the flame is extinguished. Each experiment group is repeated three times. The specific conditions are shown in Table **1**.

Table 1 Experimental conditions with different numbers of spray holes and spray heights

Number of spray holes	Spray height	Experiment number
4	30cm	D_1
	25cm	D_2
	20cm	D_3
8	30cm	D_4
	25cm	D_5
	20cm	D_6

3. Analysis of experimental results

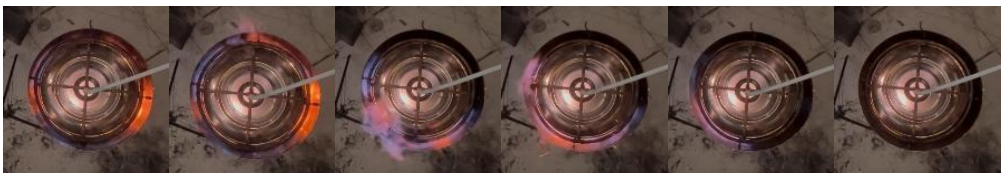
Since the temperature change of the flame was clearly recorded by the thermocouples at a height of 10 cm from the bottom of the storage tank, to eliminate the influence of local non-uniform melting, the average value of the temperature data from the thermocouples on both sides of this height was used.

3.1 Analysis of fire extinguishing effects at different spray heights with 4 holes

3.1.1 Flame morphology and fire suppression time

Since the melting point of EVA hot-melt adhesive is only 80 °C, all the spray holes melt almost simultaneously. Figure **2** shows the dynamic evolution of the flame during the fire extinguishing process at different spray heights, with the device responding rapidly. At different spray heights, the EVA hot-melt adhesive melts, and the flame intensifies instantly. In the early stage of CO_2 injection, the encoiling disturbance and fuel re-evaporation trigger the premix effect, transforming the stable diffusion combustion into semi-premix or premix combustion, and significantly increasing the flame height and intensity. As CO_2 continues to be injected, high-concentration low-temperature CO_2 forms gas channels that disrupt flame continuity and disrupt plume structure, while inerting and diluting oxygen, gradually suppressing combustion. The startup times for the D_1, D_2, and D_3 conditions are 12, 8, and 8 seconds, respectively. Notably that the operating time of the D_3 operating unit was not further shortened due to the closer distance to the fire source. This is because ethanol combustion is gas-phase combustion, evaporation is a strong endothermic phase change. Affected by the fuel evaporative cooling effect and the local flow field, the rate of increase in ambient temperature at this height is slightly lower than that at higher altitudes. This conforms to the law of heat transfer in a non-uniform thermal field [24].

Jet height: 30cm (D_1)

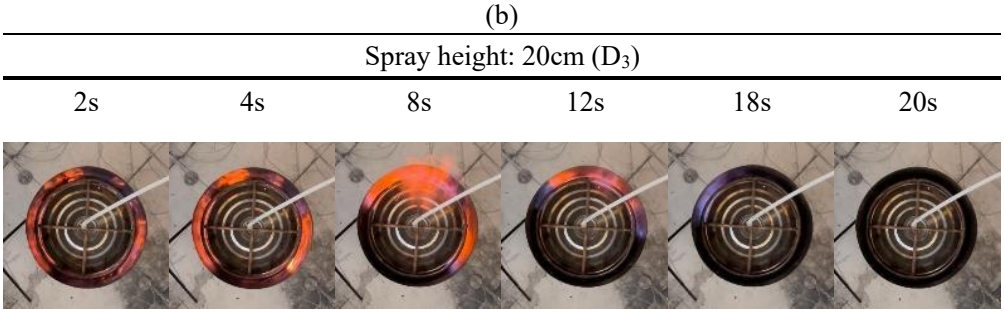


(a)

Spray height: 25cm (D_2)



(b)

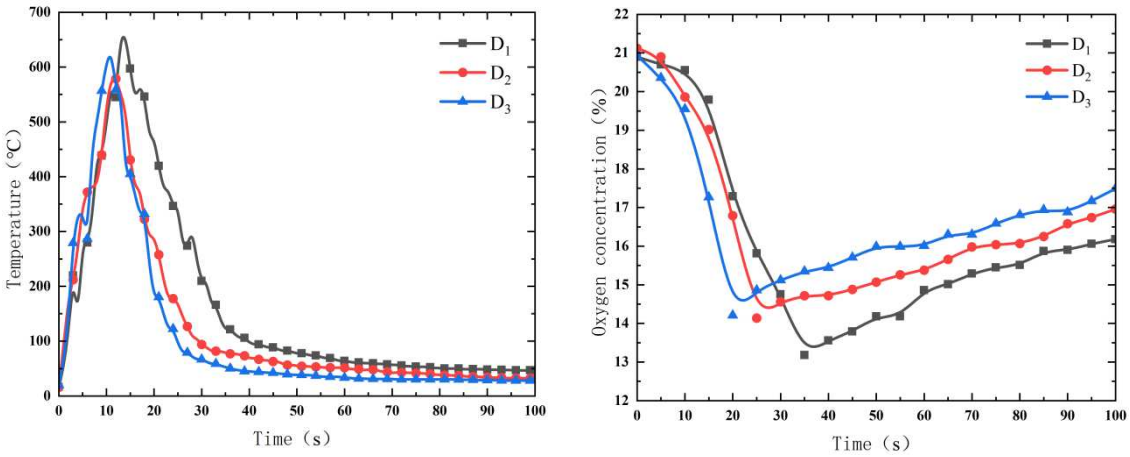


(c)

Fig. 2 Images of CO2 extinguishing ethanol ring pool fires at different spray heights with a different number of holes (a) Image of a fire flame in an ethanol ring cell at a 30cm jet height (b) Images of fire flames in an ethanol ring cell at a spray height of 25cm (c) Image of a fire flame in an ethanol ring cell at a 20cm jet height

3.1.2 Changes in temperature and oxygen concentration

As shown in the temperature curve in Figure **3**(a), a temperature peak occurs when the gel holes melt. This is because, after the gel holes melt, the shock of the low-temperature gas disrupts the fire and flow fields, thereby intensifying the ethanol vapor-oxygen mixture near the fire source and causing the flame to reach its peak quickly. Low-position spraying not only speeds up fire suppression but also accelerates overall cooling of the fire environment, which is crucial for preventing reignition and reducing thermal damage. The D_3 condition has the fastest cooling rate, reaching a peak of 630.6 °C in 11 seconds and dropping to 180.5 °C in 20 seconds, with an average rate of 50 °C /s. The D_2 condition reached a peak of 578.8 °C in 11s and dropped to 169.5 °C in 25s, with an average rate of 29.2 °C /s. Diffusion mixing was dominant at a height of 25cm. D_1: 13s peak at 658.1 °C, 35s drop to 121.2 °C with an average rate of 24.4 °C /s.



(a)Temperature change (b)Oxygen concentration change

Fig. 3 Changes in temperature and oxygen concentration of CO_2 extinguishing ethanol ring pool fires at different spray heights with different numbers of holes (a) Temperature change (b) Oxygen

concentration change

The decrease in oxygen concentration results from the combined effects of two physicochemical processes: combustion oxygen consumption and CO_2 dilution. According to the oxygen concentration curve in Figure **3**(b), the rate of decline in the oxygen volume fraction increases with decreasing jet height. According to the classical plume theory, the ascending plume formed by the pool fire will continue to exhaust and draw in the surrounding air when the top is open, and the suction capacity of the plume increases with height. However, above the flame interstitial zone, as the plume diameter expands, the central linear velocity gradually decays.

The dilution of oxygen by CO_2 can be divided into three stages: impact, thermal plume uplift, and gas displacement: high-pressure CO_2 impacts the liquid surface downward to form a local high concentration gas layer and disturb the flow field; The plume at the base of the flame rapidly sucks the CO_2 from the bottom into the updraft; The hot plume continues to draw CO_2 to the top for expulsion, and the external replenishment slowly sinks and mixes, causing the oxygen concentration at the monitoring point to drop rapidly.

Under condition D_1, the jet height is above the flame interval zone, and the plume suction capacity is weak. CO_2 is easily diluted or carried out by the supply gas flow, and the unsucked CO_2 slowly settles and diffused; In addition, the CO_2 jet released from a height of 30cm travels a long distance to the base of the flame, its momentum is severely dissipated, and it cannot form a direct and intense impact on the reaction zone near the liquid surface. The oxygen concentration drops gently to 13.18% in 30 seconds. Under D_2 condition, the jet height is near the intermittent zone, with both entrainment and sedimentation coexisting, and the rate of oxygen concentration decline is higher than that under D_1 condition, which drops to 14.14% after 25 seconds. The asphyxiation in D_3 is the fastest and most thorough. The direct, intense impact of the CO_2 jet on the liquid surface reaction zone reduces the oxygen volume fraction to 14.21% within 20 seconds, the flame is extinguished, and the oxygen concentration gradually recovers.

3.2 Analysis of fire extinguishing effects at different ejection heights with 8 holes

3.2.1 Flame morphology and fire suppression time

Figure **4** shows images of flame morphology during fire extinguishing at different spray heights under 8-hole conditions. Under Condition D_4, CO_2 is sprayed at 12 seconds. The flame first briefly intensifies, then slowly shrinks, and extinguishes in 30 seconds. The 30cm high injection results in insufficient momentum of the CO_2 jet, making it difficult to penetrate the flame plume and having a limited effect on the flame

root. In operating D_5, CO_2 is released at 8 seconds. The lower jet height increases the jet penetration and mixing efficiency, and the flame is quickly suppressed and extinguished in 20 seconds. The D_6 operation uses a low-position injection of 20cm and starts rapidly in 8 seconds. CO_2 acts directly on the base of the flame, and the flame is quickly divided and extinguished in just 15 seconds. The extinguishing times for D_4 to D_6 were 30, 20, and 15 seconds respectively, which were 14.3%, 20%, and 25% shorter than those for D_1 to D_3.

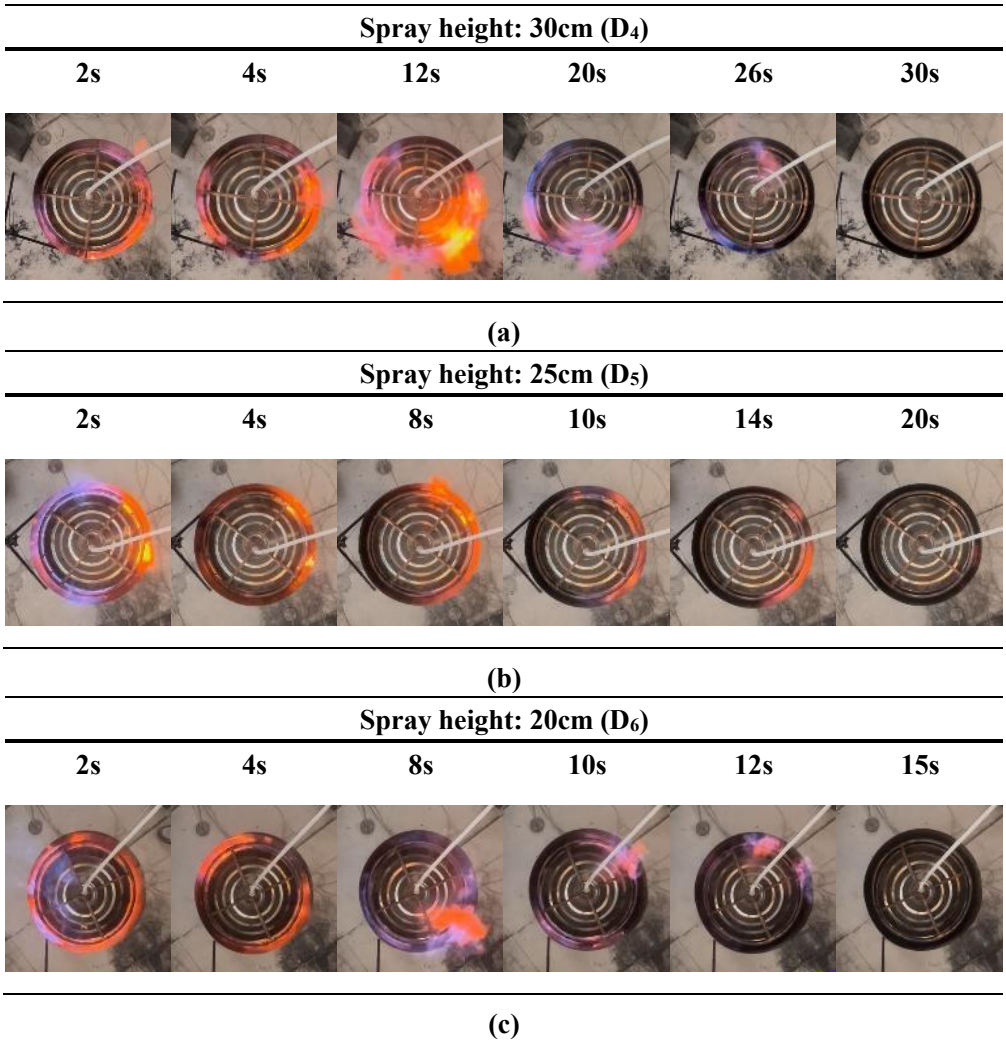
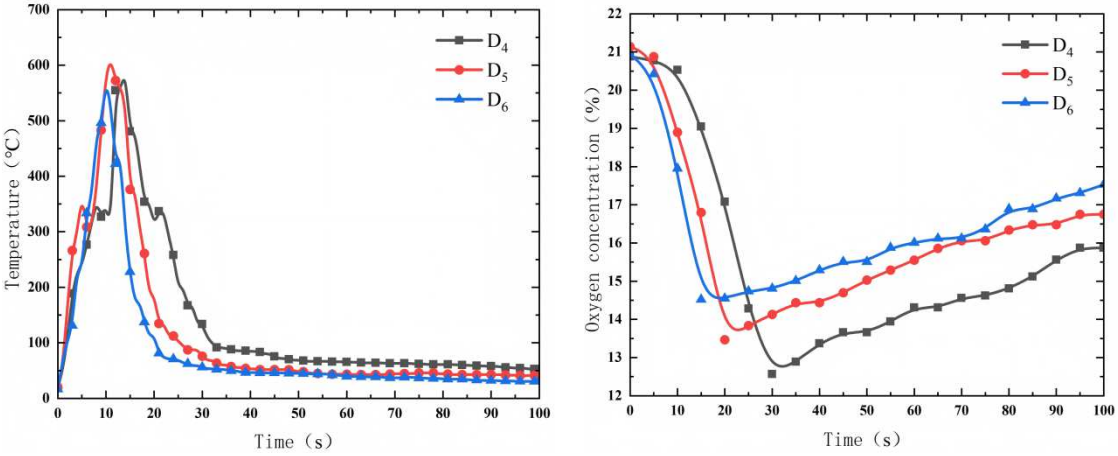


Fig. 4 Shows the flame images of CO_2 extinguishing the fire in the ethanol annular pool at different spray heights with 8 holes (a) Image of a fire flame in an ethanol ring cell at a 30cm jet height (b) Images of fire flames in an ethanol ring cell at a spray height of 25cm (c) Image of a fire flame in an ethanol ring cell at a 20cm jet height

3.2.2 Changes in temperature and oxygen concentration

Figure **5**(a) shows the temperature variation curves at different injection heights under 8-hole conditions. Under D_4 conditions, the high injection cooling efficiency is low, and CO_2 is prone to ineffective diffusion, making it difficult to act on the reaction

zone directly; The temperature peaks at 592.7 °C in 14s and drops to 133.5 °C in 30s, with an average cooling rate of 28.7 °C /s. Under D_5 conditions, the cooling effect improved significantly as the injection height decreased, with the temperature dropping from a peak of 612.5 °C at 11s to 186.7 °C at 20s, yielding an average cooling rate of 47.3 °C /s. With 20cm low-position injection and 8 holes evenly distributed in D_6 condition, CO_2 can strongly impact and evenly cover the combustion zone, achieving efficient convective cooling. The temperature drops sharply from a peak of 573 °C in 10s to 227.9 °C in 15s, with an average cooling rate of 69 °C /s.



(a)Temperature curve **(b)oxygen concentration curve**

Fig. 5 Changes in temperature and oxygen concentration of CO_2 extinguishing ethanol ring pool fires at different spray heights with 8 holes (**a**) Temperature curve (**b**) oxygen concentration curve

As shown in the oxygen concentration curve in Figure 5(b), the CO_2 dilution capacity increases as the injection height decreases, and uniform release from 8 holes can achieve efficient coverage. At high injection in condition D_4, CO_2 is difficult to displace oxygen rapidly, and dilution occurs only through slow diffusion, with the oxygen concentration dropping to 12.57% in 30 seconds. Under the D_5 condition, the injection height is reduced, the mixing efficiency is improved, and the oxygen concentration drops more rapidly to 13.47% in 20 seconds, which is significantly better than in the 4-hole condition at the same height. The low-position multi-hole injection in D_6 condition enables rapid filling of the reaction zone with CO_2, resulting in a steep drop in oxygen concentration to 14.52% in 15 seconds, achieving efficient chemical asphyxiation. The results show that the rate of decline in oxygen concentration increases with decreasing spray height. The synergy of low-position spray and porous release maximizes CO_2 transport and dilution efficiency for rapid fire suppression. This proves that the CO_2 active fire-extinguishing technology is effective for initial fire suppression of ethanol tanks.

4 Simulation Analysis

To further investigate the impact of jet height on the cooling and suffocation effects of CO_2, CFD simulations were conducted using FLUENT to analyze the flow

field conditions corresponding to K_4~K_6 in the experiment (D_4~D_6). The variation in flame temperature and oxygen concentration during the fire-extinguishing process was analyzed.

4.1 Model

A numerical simulation scenario was established based on the experimental system. The simulated physical model matched the size of the actual experimental setup. The model was built in SpaceClaim software with a computational domain of 1.2m×1.2m×2m. Given the idealized conditions, the model was configured to be fully enclosed except for the openings, and the wall boundaries were defined accordingly.

4.2 Mesh and Model Settings

Unstructured meshes were used to balance computational efficiency and simulation accuracy, and local refinement was achieved in the fuel and oxygen inlet regions. The base cell size is 5mm, and the total grid is 870,000 cells.

For the carbon dioxide fire suppression problem, a pressure-based transient model solver was used. The gravitational acceleration was set to -9.81m/s² in the vertical direction. The turbulence model selects the buoyance-corrected standard k-ε model, and the combustion model uses the vorticity dissipation model. The boundary conditions included a pressure outlet at the top of the active fire extinguishing device and a fuel and oxygen mixture inlet at the bottom, which was designated as the velocity inlet with an inlet velocity of 0.01m/s; the mass fractions of ethanol and oxygen were set at 0.0614 and 0.211, respectively. The carbon dioxide injection pressure was set as a parameter consistent with the experimental conditions. The locations of the temperature and oxygen concentration monitoring points were consistent with the experimental conditions. The initialization method selects standard initialization, and the flow field initialization parameters are listed in Table **2**.

Table 2 Flow field Initialization parameters

Boundary conditions	Parameters
Ambient temperature	25
Initial oxygen concentration	0.211
Time step	0.01 s
Maximum number of iterations per step	60
Total number of calculation steps	20000

4.3 Comparative analysis of numerical simulation and experimental results

4.3.1 Temperature flow field analysis

Figure **6** shows the changes in flame morphology at the cross-section of the

ethanol annular pool fire 20 seconds before carbon dioxide injection. The figure shows that ethanol combustion occurs only in the narrow annular region between the outer edge of the float plate and the tank wall. At 2.5 seconds, the flame spreads rapidly across the annular liquid surface, forming a thin, complete annular flame band. Due to the physical barrier posed by the floating disk, the flame cannot develop toward the center. At this point, the flame, band is thin and the flame height is low, but the transition from ignition to a stable spreading flame has been completed. At 5 seconds, the burning intensifies, buoyancy convection intensifies, the flame band thickens significantly radially, and it develops close to the outer wall of the float plate. At 10s, the radial thickness of the flame was close to the geometric limit (close to the outer wall of the float and the inner wall of the tank), the height of the flame exceeded the height of the float, and the flame front was clearly visible. At 15s, the combustion rate and fuel evaporation tend to balance, combustion is in a stable state, and the flame shape stabilizes. For up to 20s, the change in flame shape is mainly due to an increase in flame temperature and the radiation of hot flue gas, rather than an increase in scale.

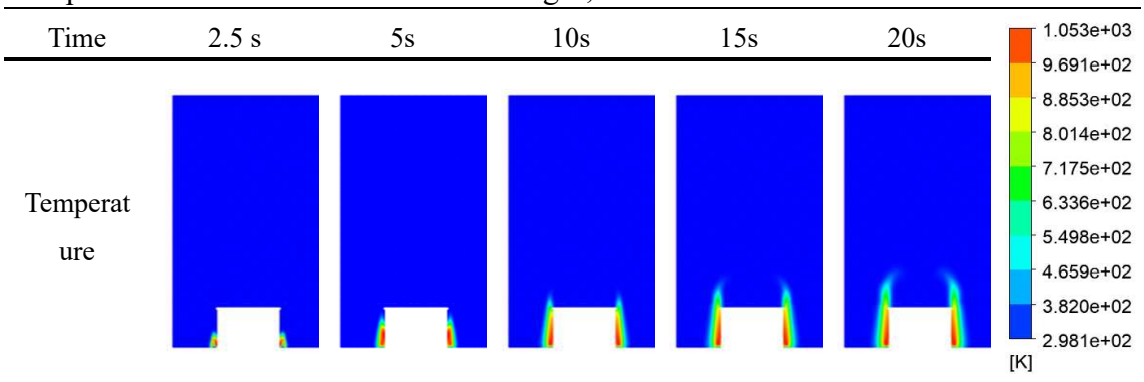


Fig. 6 Changes in flame shape when no carbon dioxide is injected

4.3.2 Analysis of Numerical simulation Results of the temperature field

The temperature simulation results at different injection heights with 8 holes are shown in Figure 7. The simulation results are in high agreement with the experimental data. The operating temperature changes over time with the following basic characteristics: Initial stage (0-5 seconds): The operating temperature rises rapidly from the ambient temperature (25 °C) to 250-300 °C, corresponding to the development and stable combustion stages of the pool fire. All conditions are consistent during this stage, indicating that the initial development of the fire is not affected by the subsequent ejection height. Peak phase (5 to 15 seconds): After the device is activated, the temperature reaches its peak. Cooling phase (after 15 seconds): Temperatures at all operating conditions continue to drop, but the rate of decline varies significantly across injection heights. The K_4 operating temperature peaks at 589.1 °C at 14s and drops to 105.3 °C at 30s. The entire cooling process is relatively gentle, with an average cooling

rate of approximately 30.2 °C /s. The K5 temperature rose to a peak of 583.3 °C at 11s and then began to drop more rapidly, reaching 143.4 °C at 20s, with an average cooling rate of about 48.9 °C /s, significantly faster than K4. The K6 temperature rose to 577.6 °C in 10 seconds and then began a very steep drop, reaching 205.9 °C in 15 seconds, with an average cooling rate of about 74.3 °C /s.

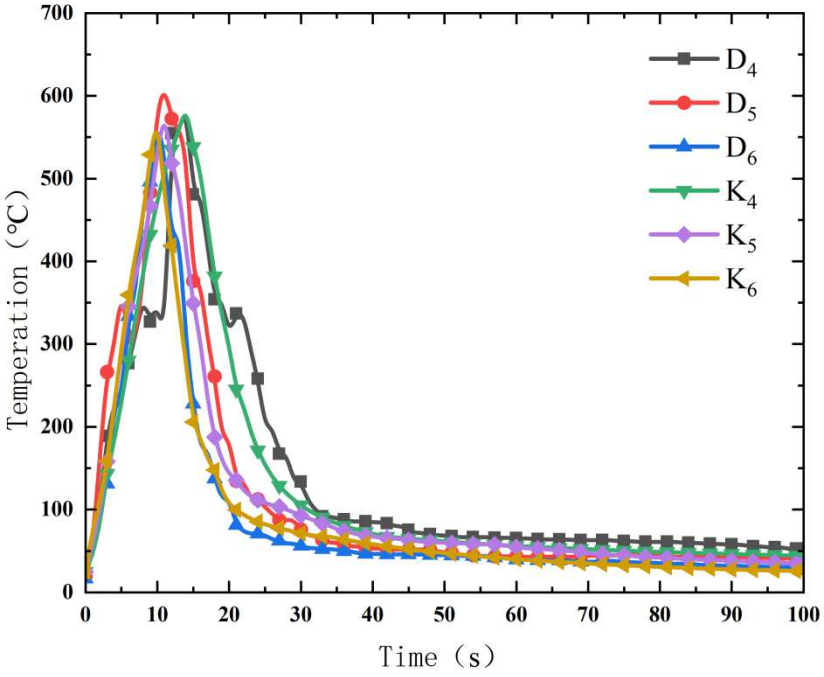


Fig. 7 Simulation and experimental temperature variation of extinguishing ethanol tank fire at different spray heights with 8 holes

4.3.3 Analysis of numerical simulation results of oxygen concentration

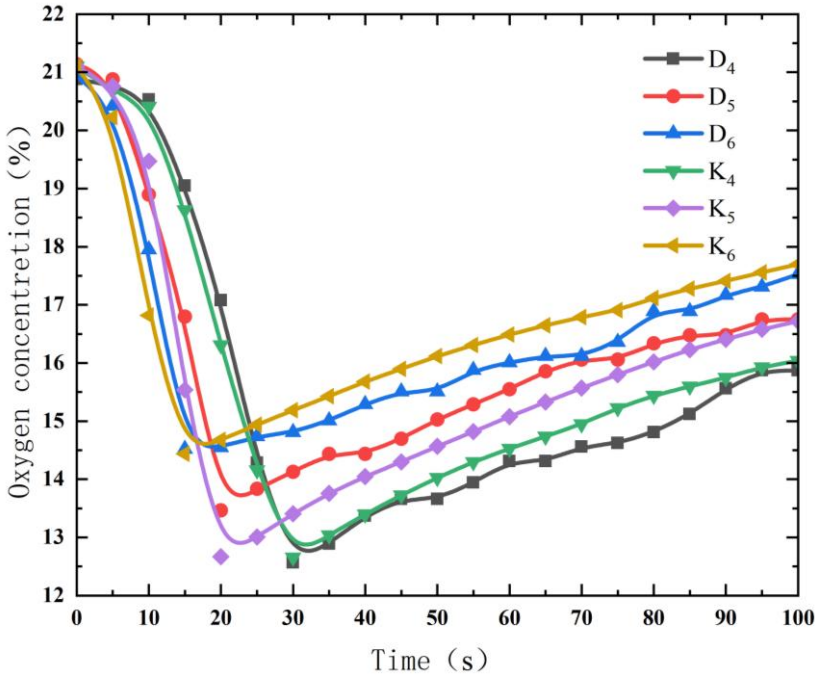


Fig. 8 Simulation and experimental changes in oxygen concentration for extinguishing ethanol tank fires at different spray heights with 8 holes

Figure **8** shows the simulation and experimental variations in oxygen concentration during the extinguishment of ethanol tank fires at different spray heights with an 8-hole nozzle. The K_4-K_6 simulation data are in line with the experimental trend. The oxygen gas integral across all conditions shows a three-stage pattern: "rapid decline - reaching the lowest point - slow recovery". The descent phase is driven by combustion consumption and CO_2 dilution, while the recovery phase is driven by the exchange of air between the top-open tank and the outside.

The critical oxygen concentration when the flame goes out under different conditions: 12.66% under K_4 condition（reached in 30 seconds); 12.67% under K_5 conditions (reached within 20 seconds); K_6 condition 12.44% (reached in 15 seconds). Reducing spray height significantly improves the extinguishing efficiency of CO_2. Low spray can achieve rapid cooling and suffocation at the base of the flame.

5 Conclusions

This paper examines the effectiveness of an independently designed fire extinguishing device for the initial pool fire in the annular gap of the tank float. The study examined the impact of spray height and the number of spray holes on the effectiveness of CO_2 fire suppression and reached the following conclusions:

(1) Carbon dioxide fire suppression systems have excellent fire suppression effects. Thanks to the diffusion and inerting effects of continuous carbon dioxide injection, it can effectively extinguish the annular flame at the edge of the storage tank. In addition, by optimizing the spray height and the number of spray holes, the fire suppression time can be reduced by 57.1%.

(2) Low-position spraying (20cm) has a better extinguishing effect on CO_2 and takes less time to extinguish compared to high-position spraying (30cm). Increasing the number of nozzles can increase the CO_2 flow rate. Eight nozzles can form a denser, more uniform spray ring, improving the CO_2 coverage of the ethanol annular pool fire, reducing the time required for CO_2 to mix evenly, and enabling the formation of an oxygen-rich environment at the base of the flame more quickly, accelerating the fire extinguishing process.

(3) The temperature field simulation was consistent with the experimental temperature curve in general. The temperature rise trend before the CO_2 injection was consistent, and the temperature peak caused by flame intensification occurred after the injection, and the decline trend was consistent. The simulation results for the oxygen concentration field were in good agreement with the experimental data, with an average error ranging from 1.86% to 3.61%, verifying the feasibility and reliability of the active carbon dioxide fire extinguishing device for initial ethanol pool fires.

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