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Full Length Article

# Early extinguishment of spontaneous combustion of coal underground by using dry-ice's rapid sublimation: A case study of application

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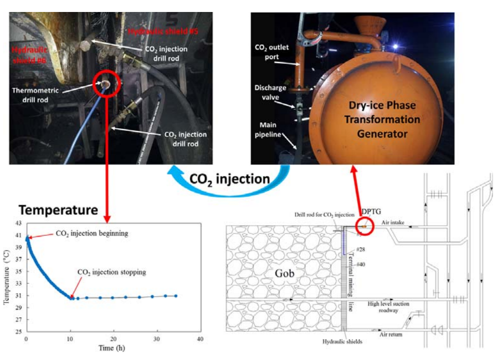
## GRAPHICAL ABSTRACT

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## ABSTRACT

Carbon dioxide injection is an ideal approach to prevent and control spontaneous combustion of coal in coal mines, which has higher purity, wider coverage and stronger inerting effect, but its application is limited by how to produce considerable gaseous carbon dioxide underground. Liquid carbon dioxide has high risks to be used underground due to its phase-state instability. Dry-ice has stable properties, but its sublimation in normally is too slow to extinguish the fire. To address this issue, a new type of apparatus for efficiently sublimating dry-ice has been developed independently, which would yield more than 205 times as much carbon dioxide as dry-ice under normal condition. There is no external power supply during its working, but the heat for dry-ice's rapid sublimation originates from continuously running water in a copper pipe inside the apparatus, thereby greatly improving the security of the use underground. This apparatus has been successfully applied to extinguish several early spontaneous combustion in Yangmeiwu Coal Mine in China. This paper describes the apparatus and its application.

## 1. Introduction

Smoldering fire of coal is a major hazard for coal mining underground [1], most of which occurs in mined-out areas and top-coal caving region of roadways [2,3]. The spontaneous combustion results from multi-physics coupling effects, involving air seepage, oxygen transport, heat generation and transfer [4–7], which not only produces a large amount of toxic gases, but is also one of the culprit for gas explosion underground [8]. Moving at the speed of sound, pressure wave resulting from the gas explosion lifts the deposited coal dust into

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**Table 1**
Comparison of various mine fire control technologies.

| Technology | Raw materials | Advantages | Weaknesses |
|---|---|---|---|
| Thick loess grouting | Yellow mud or fly ash mixed with water | 1. Isolation coal with oxygen by wrapping up floating coal<br>2. Cooling hot coal down<br>3. Cost-efficient | 1. Flowing only to low-lying areas, the slurry cannot reach the coal at high position<br>2. Small and uneven coverage on floating coal in longwall gobs |
| Water injection | Mine water or tap water | 1. Fast cooling<br>2. Reducing oxygen concentration in burning area by water vapour<br>3. Lowest cost | 1. Difficult to stay on high position<br>2. Easy to form pools, thereby worsening the working environment<br>3. Enhancing coal self-ignition ability after complete evaporation of water |
| Spray inhibitor | $CaCl_2$, MgCl or NaCl | 1. Forming an aqueous liquid film on surface of coal to isolate oxygen<br>2. Inhibiting surface activity of coal | 1. Difficult to cover floating coal in large area<br>2. Etching equipment<br>3. Inhibition failure after evaporation of water |
| Inert gas injection | $N_2$ or $CO_2$ | 1. Reducing oxygen concentration in fire zone<br>2. Eliminating risks of gas explosions in fire zone<br>3. Larger coverage<br>4. No corrosion<br>5. Cost-efficient | 1. Easy to diffuse with air leakage, inert gas cannot remain in fire zone for a long time<br>2. No cooling effect in $N_2$ injection |
| Gelatum infusion | $NaSiO_3$ and Ammonium salt;High molecular gelatum | 1. Good plugging on air leakage<br>2. Good cooling effect<br>3. Effectively extinguishing the small fire zone | 1. Give off ammonia, a toxic gas<br>2. Small flow rate and poor mobility<br>3. Poor heat resistance<br>4. Expensive |
| Leaking stoppage | Polyurethane foam;High moisture quick set slurry material | 1. Short solidification time<br>2. Good plugging on air leakage | 1. Very expensive<br>2. No fire-resistant in Polyurethane foam<br>3. Poor flow ability |

the air. Then gas flame reaching the coal dust may cause a more severe dust explosion in underground coal mine [9–11]. However, oxygen plays the most crucial role in coal self-heating/ignition [12,13]. Generally, only when ambient oxygen concentration is larger than 8% can coal be self-ignited; when below 6%, coal goes into the state of suffocation so that oxidation reaction of coal is greatly suppressed [14], which is the basic principle for developing prevention technologies of coal self-ignition.

No matter predicting progression of spontaneous combustion by index gas [15–20] or detecting high temperature zones through temperature measurement [21,22] and numerical simulation [23–25], the final foothold is to take measures to prevent and extinguish the fire. There are several traditional fire-fighting technologies for coal self-ignition in underground coal mines, including thick loess grouting, water injection, spray inhibitor, inert gas injection, gelatum infusion and leaking stoppage [26–29]. A comprehensive overview has been created on these technologies in the aspects of raw materials, advantages and weaknesses by using the information from Refs. [30–32], shown in Table 1. It can be found that each technology has its limitations, but the inert gas injection is more practical, which eliminates the spontaneous combustion by minimizing oxygen concentration of fire zone, with the strengths of wide coverage, large gas-injected capacity and high prevention efficiency. Thus, this technology has been widely used, not only to put out open flame, but also to inhibit hidden fire. Most of coal mines in China have been equipped with underground mobile nitrogen making machines [33]. Moreover, some newly developed firefighting technologies, for instance the three-phase foam [31], also use the inert gas as a raw material.

Two kinds of inert gas materials are commonly applied, i.e. nitrogen ($N_2$) and carbon dioxide ($CO_2$). Some studies have evaluated their respective effects on spontaneous combustion or coal fire [34,35]. In this paper, a comparison between them on fire-fighting properties is conducted and shown in Table 2. As can be seen, relative to $N_2$ injection, $CO_2$ injection has higher purity, wider coverage, better cooling and inerting effect, while its properties of inflaming retarding and explosion suppression are stronger. The most commendable aspect is that the capacity of coal to adsorb $CO_2$ is usually as 10 times as to adsorb oxygen [36], whereas the adsorption of coal to $N_2$ is much lower [37]. If there is carbon dioxide in the surrounding environment of coal, it will preempt activating adsorption vacancies of coal surface to make oxygen adsorption decrease, thereby to fundamentally weaken or hinder the coal-oxygen reaction. Moreover, $CO_2$ injected into underground mined-out areas can not only reduce greenhouse gas emissions, but also increase methane extraction [38]. Thus, more and more attentions have been paid to $CO_2$ injection underground.

Gaseous $CO_2$ obtained by chemical reaction of sulfuric acid with sodium bicarbonate had been used to prevent spontaneous combustion underground in China [39], but its application was limited due to the high cost and small output. After that, some coal mines in China tried to use liquid carbon dioxide to control fire hazard [36]. The liquid carbon dioxide was stored in a high pressure tank and transported to the underground fire site by tramcars. The gaseous $CO_2$ was produced by reducing the pressure of tank to evaporate the liquid, and then it was injected into the fire zone. However, the evaporation of liquid carbon dioxide needs to absorb a larger amount of heat, about 577.8 KJ/kg, which is highly possible to solidify some of the liquid into dry-ice soon, resulting in the blockage of gas outlet. Besides, there are high risks in transporting and operating the liquid carbon dioxide underground as well. Thus, this technique has also not been widely applied. Compared with the extreme instability of liquid carbon dioxide, dry-ice is stable and easy to be transported. 1 $m^3$ of dry-ice can expand into about 851 $m^3$ of gaseous $CO_2$ under normal condition (20 °C, 0.1 MPa), but its sublimation rate is too small, about 0.0017 ($m^3$ $CO_2$)/min, to meet the requirements of mine fire control. Therefore, the sublimation of dry-ice in a safe and efficient way has become a bottleneck for the development of underground fire-fighting technology.

To address above issue, a new apparatus has been developed independently to heighten the sublimation rate of dry-ice by 205 times. This apparatus has been successfully applied in Yangmeiwu Coal Mine in China to extinguish several early spontaneous combustion of coal underground.

## 2. Dry-ice phase transformation generator

### 2.1. Description

In our work, a new invention apparatus has been designed and manufactured to make dry-ice fast sublimate so that a large amount of $CO_2$ can be produced in a short time, referred to as Dry-ice Phase Transformation Generator (DPTG). This apparatus is characterized by