Original Research Article

A review of current technologies for the oxidation treatment of low-concentration coal mine methane

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Abstract: Methane has a strong greenhouse effect. Low-concentration coal mine gas is hard to utilize directly, posing a major challenge for emission reduction and energy recovery. Regenerative Thermal Oxidation (RTO) can efficiently treat ultra-low-concentration methane and recover waste heat. This paper reviews the oxidation technologies of low-concentration coal mine gas, focuses on the principle, features and engineering applications of RTO, and verifies its advantages via typical cases. Finally, the development prospects of RTO are discussed, providing a reference for low-carbon and efficient utilization of coal mine gas.
Keywords: low-concentration methane; regenerative thermal oxidation; RTO; methane emission reduction; waste heat recovery

1. Introduction

Methane has a global warming potential approximately 25 times that of CO_2[1-2] and has a significant impact on climate change. Ventilation air methane (VAM) from coal mines is characterized by high emission volumes, low concentrations, and significant fluctuations in flow rates, making it a key focus and challenge in methane management. Although this gas must be continuously vented to ensure mine safety, its relatively low methane concentration still holds high potential for resource utilization. Rational utilization can simultaneously achieve greenhouse gas emission reductions and efficient energy recovery. Regenerative Thermal Oxidation (RTO) technology is well-suited for low-concentration, high-flow gas streams and has demonstrated excellent stability and economic viability in engineering applications.

This paper reviews the research progress and engineering applications of oxidation technologies for low-concentration coal mine gas, focusing on principles and technical features. Based on typical cases, it explores optimization paths and prospects the efficient utilization and industrial development of coal mine gas.

2. Physicochemical properties and management challenges of low-concentration coal mine methane

Low-concentration coal mine methane typically refers to methane volume fractions $\varphi(CH_4) < 30\%$, with the methane volume fraction in mine exhaust air (Ventilation Air Methane, VAM) often below 1% [3]. In terms of physical properties, this gas is characterized by a low calorific value, high flow rate, and significant fluctuations in composition. Methane content typically ranges from 0.1% to 1.0%, far below the flammability limits of 5%–15%, making it difficult to ignite directly or sustain stable combustion. Furthermore, due to the influence of ventilation systems, the exhaust gas exhibits characteristics such as high flow volume, high velocity, low temperature, and high humidity, which not only increase the difficulty of collection and transmission but also impose higher demands on subsequent oxidation treatment and energy recovery. In terms of chemical properties, the oxidation reaction of low-concentration methane is slow and requires high activation energy, necessitating external heat supply to sustain the reaction [4–5]. Its treatment primarily faces four challenges:

(1) Poor energy self-sufficiency. Low-concentration coalbed methane has a low calorific value,

requiring external heat input for oxidation reactions, resulting in high system energy consumption and poor economic efficiency.

(2) Significant concentration fluctuations. Due to variations in mine operating conditions, coalbed methane concentration and flow rate fluctuate widely, making conventional processes ill-suited and limiting operational stability.

(3) Stringent safety control requirements. In high-flow, high-oxygen environments, localized concentration anomalies or equipment overheating can easily trigger fire or explosion risks.

(4) Low level of resource utilization. A high proportion of mine exhaust gas is discharged; without cascaded utilization, this can easily lead to energy waste and greenhouse gas emissions.

2.1. Types and principles

Oxidation technologies for low-concentration coal mine methane primarily include regenerative thermal oxidation (RTO), catalytic thermal oxidation (CTO), and regenerative catalytic oxidation (RCO). Among these, CTO has relatively low thermal efficiency and is difficult to scale up, while RCO is limited by the heat resistance of the catalyst and has low waste heat utilization efficiency; both have been gradually phased out. RTO achieves the safe destruction of methane and waste heat recovery through high-temperature oxidation. It consists of an oxidation unit, a heat storage unit, and a safety temperature control unit, and operates continuously based on a heat storage–oxidation–heat exchange cycle. After pretreatment, the gas enters the heat storage chamber and is preheated to approximately 800 ℃, then fully oxidized in the combustion chamber at 850–950 ℃; The high-temperature flue gas releases heat and cools down in another heat storage chamber. Through valve switching, the heat storage media undergo periodic heat absorption and release, enabling stable treatment of gas streams with a volume fraction as low as 1%–2%. This technology still faces challenges in areas such as high humidity, concentration fluctuations, and energy utilization efficiency.

2.2. Technical features and advantages

RTO equipment can be broadly categorized into three types: two-chamber RTO, three-chamber RTO, and rotary valve RTO:Two-chamber RTOs alternate heat storage and release through two chambers and valve switching, enabling preheating, oxidation, and heat recovery with simple structure and low cost, suitable for stable gas flow. Three-chamber RTOs add a purge chamber to reduce unoxidized exhaust during switching. Rotary valve RTOs adopt a rotary valve to cut leakage risk and improve stability, with methane destruction rate exceeding 99.8% [10] and reduced external energy consumption. All three types follow the "heat storage–oxidation–heat exchange" mechanism to achieve methane emission reduction and thermal energy recovery, supporting cascade energy utilization with good safety, economy, and environmental adaptability for various working conditions.

2.3. Engineering applications and advances

The Huangbaizi Project of Wuhai Energy, a subsidiary of the State Energy Group, employs ultra-low-concentration coalbed methane (CBM) oxidation and heat recovery technology to blend low-concentration CBM (3%–12%) into a mixture of 1.2%–1.25% for high-temperature oxidation, producing 1.25 MPa saturated steam. During the 2024–2025 heating season, the project supplied 9,019.5 tons of steam and reduced CO_2 emissions by approximately 15,000 tons. Shanxi Lu'an Yuwu Coal Industry uses a rotary valve-type RTO to treat 2%–6% coalbed methane, achieving a methane destruction rate of ≥99%. Energy consumption is reduced by 40% compared to traditional two-chamber RTOs, enabling near-zero emissions from coalbed methane extraction.

3. Summary and outlook

RTO technology can efficiently treat low-concentration coalbed methane and recover waste heat, and its engineering applications are mature and stable. In the future, efforts should focus on optimizing the compatibility of materials and systems, promoting the integration of multiple technologies, and advancing industrialization to achieve efficient, low-carbon utilization of coalbed methane.

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