

Review on CO Emission Reduction in Sintering Flue Gas Circulation

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Abstract: *Achieving ultra-low CO emissions in flue gas has become a critical challenge in sintering processes. Flue gas recirculation serves as a key technological solution that aligns with green and low-carbon transition goals while effectively reducing pollutant emissions. The source of CO in flue gas during iron ore sintering and the emission characteristics of flue gas CO during dynamic migration of sintering states were analyzed, the processes and energy-saving emission reduction characteristics of circulating sintering both domestically and internationally have been systematically reviewed, and the emission reduction mechanism of flue gas recirculation sintering in reducing CO emissions and the impact of recirculated flue gas characteristics on CO reduction were extensively discussed in this paper. These studies provide theoretical support for assisting the realization of precision flue gas recirculation sintering CO reduction process*

Keywords: Iron ore sintering; Flue gas recirculation; CO emission reduction; Green and low-carbon.

1. INTRODUCTION

Iron ore sintering is the most severe flue gas pollution process in steel manufacturing. Emissions of particulate matter, SO₂, NO_x, dioxins, and CO account for over 40% of the total gaseous pollutant emissions throughout the entire steel production process. CO in flue gas is one of the primary pollutants emitted from sintering processes. Its initial emission concentration is approximately 800 times higher than the ultra-low emission limits for particulate matter, 228 times higher than SO₂, and 160 times higher than NO_x levels. CO has a greater impact on air quality than sulfur dioxide (SO₂), becoming the third-generation pollutant in sintering flue gas and has been included in the taxation scope.

Flue gas recirculation sintering is an economically viable technology that effectively reduces pollutant emissions from sintering processes. As it aligns with the requirements of high-quality development in green and low-carbon transition, this approach has gained widespread recognition within the steel industry. A portion of the sintering flue gas is selectively returned to the hot air hood of the sintering machine's fabric, the proportion of solid fuel and the flue gas emission per unit sintered ore have been reduced by utilizing flue gas waste heat and CO latent heat in flue gas recirculation sintering. Furthermore, flue gas recirculation can also overcome the issues of insufficient strength and low yield in conventional sintering processes by reducing the cooling rate of upper sintered ore. While improving the quality of sintered ore, significant energy-saving and emission-reduction effects were also achieved, flue gas recirculation sintering has attracted extensive attention and emphasis. Numerous studies have indicated flue gas recirculation sintering technology has made outstanding contributions to achieving ultra-low emissions of pollutants such as particulate matter, SO₂, and NO_x through flue gas co-control. Sintered ore can adsorb approximately 40% to 60% of particulate matter emissions. Flue gas recirculation sintering can reduce SO₂ generation through increasing SO₂ partial pressure, inhibiting sulfur oxidation and sulfate decomposition, reducing Solid Fuel Consumption by Utilizing Waste Heat and Latent Heat, and SO₂ combining with free CaO to form sulfates at a certain temperature. However, there is relatively limited research on how to reduce CO emissions through flue gas recirculation sintering. Current research on flue gas CO primarily encompasses the formation mechanism and emission patterns of CO in iron ore sintering flue gas, the effects of combustion characteristics, surface perforation, and steam injection synergistic oxygen-enriched circulation on CO emission characteristics were analyzed, and the redox reaction mechanisms of CO with NO and SO₂, as well as the catalytic gas-phase oxidation behavior of flue gas CO mediated by water vapor, sintered ore, and additives were elucidated.

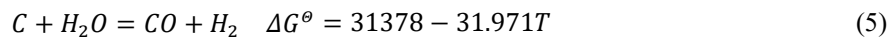
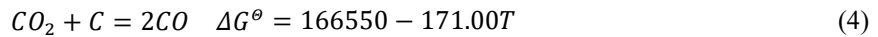
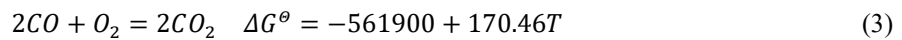
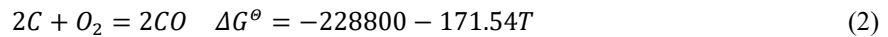
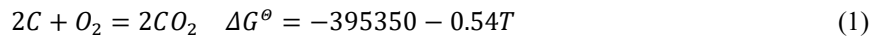
This paper elucidates the source and emission characteristics of CO in flue gas during iron ore sintering, reviews domestic and international technologies for circulating sintering processes along with their energy-saving and emission-reduction features, and focuses on discussing the emission reduction mechanisms of circulating flue gas sintering for CO mitigation, as well as the impact of circulating flue gas characteristics on CO emission reduction. These studies provide theoretical support for assisting the realization of precision flue gas recirculation sintering

CO reduction process.

2. SOURCE OF CO IN SINTERING FLUE GAS

Iron ore sintering refers to the thermal agglomeration process in which iron ore powder, recycled ironmaking products, fluxes, slag-forming agents, and solid fuels (coke) are mixed and ignited on a sintering machine to ultimately form solid blocks [1]. The CO in flue gas generated during iron ore sintering primarily originates from fuel combustion, which are comprised of incomplete combustion of gaseous fuels such as blast furnace gas, converter gas, and coke oven gas used during sintering ignition, as well as unorganized emissions from gas pipeline valves and solid additives like coke powder and coal powder incorporated into sintered mixtures [2,3]. The CO in flue gas generated during iron ore sintering from the decomposition of carbonates in the material only a small fraction originates [4,5]. Liu et al. [3] pointed out that due to the large volume of blast furnace gas during ignition, there exists a situation where CO from the ignition process undergoes incomplete combustion and directly enters the sintering main flue. However, compared to the original CO emission concentration in sintering flue gas, the amount of CO entering the main flue from incomplete combustion during ignition is minimal. In other words, incomplete combustion of solid fuels is the primary cause of high CO mass concentration in sintering flue gas.

The solid fuels primarily used in iron ore sintering include coke and anthracite. The main products of anthracite pyrolysis are volatile components such as CO, CO₂, and gaseous hydrocarbons, along with coke. The volatile components of coke powder mainly consist of CO₂ and H₂O, while the CO generated from the volatile components of anthracite and coke powder can be disregarded. The CO in flue gas mainly originates from the combustion of coke [3]. In the iron ore sintering process, coke is dispersed irregularly and randomly within the material layer, exhibiting combustion characteristics that lie between monomer coke particle combustion and coke particle layer combustion, classified as a heterogeneous reaction. After sintering ignition, carbon in solid fuel primarily undergoes the following five combustion reactions [6], which are conducted simultaneously [7].



Due to the varying Gibbs free energies of the reactions at different temperatures, the duration and reaction intensity of each reaction also differ [8]. After ignition initiation, the temperature of the sintered material layer begins to rise. Zhong et al. [4] observed that when temperatures reach 500–700°C, carbon enters a red-hot state without initiating carbon-oxygen combustion reactions. At 700°C, coke combustion commences, with both Reaction (1) and Reaction (2) occurring simultaneously, though Reaction (1) for CO₂ formation predominates. Beyond 727°C, the carbon-oxygen combustion reaction (2) for CO generation becomes more favorable, demonstrating that higher sintering temperatures increase CO production rates as illustrated in Figure 1.

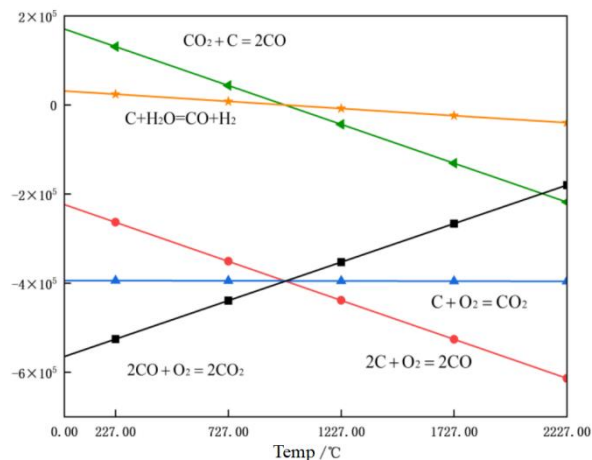


Figure 1: Effect of temperature on Gibbs free energy of reaction

The presence of water vapor creates favorable kinetic conditions for CO combustion. When entering the combustion zone, water vapor reacts with carbon through the water-gas reaction [9], triggering a hydrogen-activated chain reaction that accelerates intense CO oxidation and induces detonation. Sintering test results demonstrate that under humid conditions, CO gas-phase oxidation reactions begin at temperatures of 650°C, with continuous and stable oxidation occurring at temperatures of 700°C and above [10]. Furthermore, under the action of negative pressure suction, air flows downward through the sintered material layer. The oxygen-containing gas medium contacts the coke surface at a specific flow rate, reacting according to the convective diffusion gas-solid two-phase mass transfer model. This process inevitably creates a gas-phase boundary between carbon and oxygen, which influences oxygen access to the reaction interface and the escape of gaseous products from it. The combustion efficiency of carbon is not only temperature-dependent but also diffusion-controlled by O₂ and CO₂ [11], indicating strong correlations with the atmosphere and airflow conditions within the sintering process material layer. The sintering material layer contains minimal carbon content, resulting in weak oxidation conditions during combustion reactions as pulse rocks surround coke particles [7]. Upon ignition, coke releases substantial heat, forming a combustion zone with temperatures ranging from 1200–1500°C [12]. High-temperature exposure causes material softening and melting within this zone, where liquid phases bond sintered materials into clumps. This encapsulation of coke particles by molten residues reduces material permeability, exacerbating oxygen deficiency [7]. The prevailing weak oxidation atmosphere during sintering thus constitutes another primary cause of incomplete carbon combustion producing CO. Additionally, iron ore sintering operations employing negative-pressure draft systems generates high gas flow velocities, forcing incompletely burned CO into the main flue for direct emission, thereby increasing CO release volumes.

3. 2 EMISSION CHARACTERISTICS OF CO IN SINTERING FLUE GAS

During iron ore sintering processes, the material layer undergoing sintering can be sequentially divided into five distinct zones from top to bottom based on temperature ranges and associated physicochemical phenomena: sintered ore zone, combustion zone, drying preheating zone, overwet zone, and raw material zone. The sintering process can be characterized by six distinct states according to the evolution of these zones: State I (initial ignition forming combustion and drying preheating zones), State II (comprising all five material layers), State III (disappearance of raw material zone), State IV (elimination of overwet zone), State V (termination of drying preheating zone), and State VI (complete combustion zone disappearance). The emission patterns of CO in flue gas are intrinsically linked to these six sintering states [13], as illustrated in Figure 2.

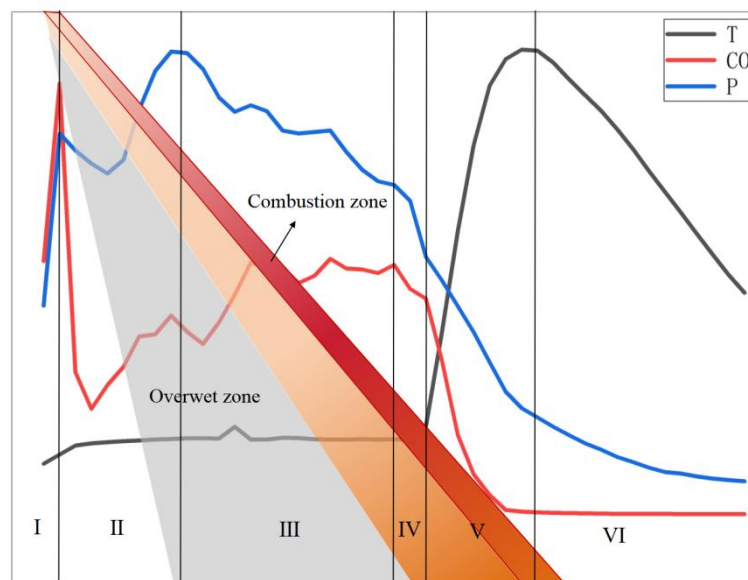


Figure 2: Variation process of sintering state and CO emission pattern in flue gas

When the sintering process is in State I, as ignition progresses, the combustion zone and drying preheating zone gradually form and thicken. The carbon combustion reaction intensifies, resulting in increased CO emissions in flue gas with a sharp rise in CO mass concentration reaching a peak value. After ignition cessation, large amounts of air enter the sinter layer through negative pressure extraction, enhancing the oxidation atmosphere and ensuring complete carbon combustion, leading to a rapid decline in CO concentration [7]. During State II, the thickness of

the combustion and drying zones remains constant. However, continuous forced-air sintering causes increased material softening and melting, resulting in expanded molten phase and thickening of the overwet zone. This reduces material permeability, weakens the oxidation atmosphere, and causes incomplete combustion, with CO rapidly rising to high concentration levels [7]. In States III and IV, combustion stabilizes with sustained CO concentration in the high range. State V sees disappearance of the overwet zone, increased sintered mineral layer proportion, and gradual reduction of combustion and drying zones. Material permeability significantly improves, oxidation atmosphere strengthens, and carbon combustion becomes complete, causing CO concentration to drop sharply. After State VI, the combustion zone gradually disappears, completing sintering with CO concentration approaching 0 mg/m³. The CO mass concentration in flue gas from sintering machine 1# at a steel plant was measured using a UV differential flue gas analyzer. The test data revealed that among the 24 air boxes of the sintering machine, the 2# air box exhibited the highest CO mass concentration emissions. The CO concentration in the 3# air box showed a significant decrease compared to the 2#. CO emissions from the 4# to 17# and 18# air boxes consistently maintained high concentrations around 8,500 mg/m³. The CO concentration in the 19# air box rapidly declined to approximately 2,200 mg/m³, while emissions from the 22#, 23#, and 24# air boxes dropped below 800, 560, and 350 mg/m³, respectively. The observed variations in flue gas CO concentrations align with the CO emission patterns corresponding to six distinct states of the sintered material layer. Yang et al. [14] conducted sintering cup experiments to investigate the impact of surface perforation on flue gas CO emissions. Their findings revealed that perforation on sintered material surfaces increased ignition depth and expanded ignition area, thereby enhancing CO combustion in the ignition gas. This process reduced the peak CO mass concentration during the first combustion phase. After ignition termination, blast furnace gas ceased participating in combustion reactions, resulting in a rapid decline in CO concentration during the subsequent combustion phase. Wu et al. [15] discovered through sintering cup experiments using oxygen-enriched ignition that oxygen-enriched ignition can effectively reduce the peak mass concentration of CO. Therefore, modern sintering processes typically employ oxygen-enriched ignition or a combination of oxygen-enriched ignition with local flue gas recirculation at the sintering machine head to minimize CO emissions from the head section of the sintering machine. In actual sintering processes, besides oxygen-enriched ignition, various adjustments are implemented including additive use [16], coke powder particle size modification, steam injection, reduced carbon charge, and flue gas recirculation [17]. These optimized sintering techniques effectively reduce CO emissions while maintaining the original emission pattern: CO levels initially surge rapidly to peak concentrations, then decline sharply before gradually stabilizing at high concentrations. After a sustained period of fluctuation, emissions eventually drop to zero upon sintering completion.

4. RESEARCH STATUS OF CO EMISSION REDUCTION IN FLUE GAS CIRCULATION SINTERING

This section primarily reviews the processes and energy-saving characteristics of circulating sintering both domestically and internationally, and discusses the current research status on reducing flue gas CO emissions by sintering atmosphere, low-valent iron oxides in sintered ore, and calcium ferrite.

4.1 Flue Gas Circulation Sintering Process

Flue gas recirculation sintering is an innovative sintering method that reuses sintering flue gas by circulating it back to the sintering material surface [18], categorized into external flue gas recirculation sintering and internal recirculation sintering. External flue gas recirculation involves diverting part of the main exhaust fan's flue gas to the trolley material surface for sintering, while internal recirculation channels flue gas from certain air box branch pipes of the sintering machine to the trolley surface. The external recirculation process features relatively simple workflow and lower fixed investment, but results in lower flue gas temperature and oxygen content, with moderate thermal efficiency and pollutant reduction performance. Internal recirculation technology, though more complex and requiring higher system operational loads, delivers elevated flue gas temperature and oxygen levels, flexible control based on flue gas characteristics, and high flue gas recycling efficiency. This section primarily discusses internal flue gas recirculation sintering technology, hereinafter referred to as flue gas recirculation sintering.

The primary objective of developing flue gas recirculation sintering was to reduce pollutant emissions while utilizing residual heat and latent heat from flue gas to enhance production capacity and achieve energy conservation [18]. In 1978, U.S.-based Wilton Steel Company pioneered the use of sintering exhaust gas recirculation combined with gravel layer filtration technology, significantly reducing suspended fine particles and hydrocarbons emitted into the atmosphere [19]. In 1981, Japan's Sumitomo Metal Industries Corporation first implemented a flue gas recirculation system, diverting post-sintering flue gas to the front section of sintering

machines. In 1992, Japan's Nippon Steel Corporation developed regional flue gas recirculation technology through equipment upgrades, utilizing 5% of flue gas from the sintering head and 20% from the tail section for recirculation. Subsequent advancements included the EOS (external recirculation), LEEP, and EPOSINT flue gas recirculation processes developed by Dutch company Emerytten in 1994, HKM in 2001, and Siemens-OSTAL in 2005 [20]. In 2013, China's Baosteel Group introduced its proprietary BSFGR flue gas recirculation sintering process. These representative flue gas recirculation sintering processes have achieved significant energy conservation and emission reduction effects (Table 1) while maintaining sinter quality and production output, thanks to their unique technical characteristics, earning widespread recognition in the steel industry.

Table 1: Comparison of Energy Conservation and Emission Reduction Effects in Typical Flue Gas Circulation Sintering Process

Name of Flue Gas Circulation Sintering Process	Flue gas recirculation rate/ %	Flue gas pollutant reduction rate/ %				Energy-saving effect	
		stive	SO ₂	NO _x	Dioxin	fractional energy saving/ %	Carbon reduction amount/(kg/t)
Regional flue gas recirculation	28.1	40	—	52.4	70	5.5	3.2
ESO	55.6	45	41.3	1.5	—	20	12
LEEP	45	50	67.5	75	90	14.2	7
EPOSINT	25~28	30	28.9	23.5	30	4.4~11.0	2~5
BSFGR	25~35	35	12.93	31	35	3~6	2~4

Subsequently, major steel enterprises in key regions including Xinxing Cast Pipe, Yongyang, and Handan Steel adopted BSFGR and EOS process technologies to upgrade sintering equipment [21]. Against the backdrop of green and low-carbon transformation requirements for iron ore sintering, pioneering the development of proprietary sintering processes that integrate "high-efficiency waste heat recovery with flue gas recirculation" will undoubtedly establish core competitiveness for enterprises [18].

4.2 Mechanism of CO Reduction in Flue Gas Circulation Sintering

The efficient utilization of flue gas waste heat and latent heat can also reduce solid fuel consumption and decrease CO emissions from sintering flue gas. Current studies indicate that cyclic sintering can return flue gas CO as fuel to the high-temperature zone for CO combustion reactions [15], thereby reducing CO emissions. The sintering process is generally characterized by an oxidative atmosphere, while a localized high-temperature zone surrounding the fuel exhibits a reductive atmosphere. CO is a typical reducing agent, the reduction reaction of NO is intensified by a sintering atmosphere characterized by high temperature, high CO, and low oxygen in flue gas recirculation sintering [22-25]. Experimental results indicate that the most effective CO reduction $2CO + 2NO = N_2 + 2CO_2$ of NO in circulating sintering flue gas occurs at medium temperatures between 600 and 800°C. When temperatures exceed 800°C, CO primarily undergoes secondary combustion reactions [26]. During flue gas recirculation, low-valent iron oxides (Fe₃O₄, FeO) and calcium ferrite (CaFe₂O₄) in sintered ore can be fully utilized to catalyze the CO reduction of NO reaction [22,23]. Under the action of calcium ferrite, the activation energy for CO reduction of NO decreases from 246.68 kJ/mol to 138.80 kJ/mol [9].

4.3 Impact of Circulating Flue Gas Characteristics on CO Emission Reduction

Flue gas recirculation sintering is a sintering technology that selectively returns part of the sintering flue gas through pipelines to the hot air hood of the sintering fabric for reuse under the action of a recirculation fan. There are two key issues for effectively reducing CO emissions through flue gas circulation sintering how to select appropriate flue gas extraction position, return material surface position, and optimal flue gas circulation volume based on sintering status and flue gas CO emission characteristics. The characteristics of circulating flue gas—high temperature, high moisture, and low oxygen content—can affect sintered ore quality by altering the O₂ content in the sintering atmosphere [27]. Excessive flue gas temperature causes thermal expansion of gases, reducing the effective O₂ content in the sintered material layer [28]. Excessive flue gas humidity exacerbates over-wetting of the material layer [18]. An excessively high flue gas recirculation rate reduces the O₂ content in multi-component mixed sintering atmosphere, exacerbates SO₂ enrichment in sintered ore, and adversely affects blast furnace production [18]. Single-factor sintering experiments demonstrate that when the oxygen content in circulating flue gas falls below 18%, combustion efficiency decreases, incomplete combustion worsens [29], and sinter quality is

compromised. The optimal flue gas temperature entering the sinter charge layer ranges from 150°C- 200°C [17]. The most suitable flue gas recirculation ratio is approximately 30% [29,30], with low-oxygen flue gas recirculation rates not exceeding 19%. The ideal flue gas recirculation coverage for sintering ranges from 23% - 35% [31]. The water volume fraction in circulating flue gas should not exceed 8% [17], while the optimal water mass fraction is 4% - 6% [9]. Sintering production practices at a steel plant demonstrate that circulating flue gas temperatures reaching up to 290°C and coke-to-powder ratios ranging from 6.0% - 5.5% do not adversely affect sintering performance indicators. Considering the service life of equipment such as recirculation fans, pipelines, and flue hoods, circulating flue gas temperatures are typically maintained below 300°C [32]. During actual cyclic sintering processes, multiple factors such as high temperature, high moisture content, and low oxygen levels in flue gas coexist and interact. Leveraging sintering conditions and flue gas emission characteristics to determine optimal cyclic sintering process parameters, along with proposing effective flue gas recycling optimization measures, plays a crucial role in achieving synergistic effects of green emission reduction, energy conservation, and improved production quality.

5. CONCLUSION

The substantial CO emissions from iron ore sintering flue gas not only pose significant environmental and public health risks but also result in substantial energy loss. Flue gas recirculation sintering represents a key technological approach that aligns with green and low-carbon transition requirements for high-quality development, effectively reducing pollutant emissions. This study provides theoretical support for developing precision-based CO reduction processes in flue gas recirculation sintering. The research primarily elucidates the sources of CO emissions during iron ore sintering and analyzes emission characteristics during dynamic sintering state migration. It reviews global recirculation sintering technologies and energy-saving features, with particular emphasis on CO reduction mechanisms and the impact of recirculating flue gas characteristics on emission control.

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