Study on pollutant emission characteristics of sludge combustion in municipal wastewater treatment plants under oxygen-enriched conditions

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Abstract: Oxygen-enriched combustion technology, as an efficient and clean combustion technology, shows great potential in the field of sludge disposal by using a high concentration of oxygen (>21%) instead of air as a combustion agent. Firstly, this paper investigates the differences in pollutant emission characteristics between sludge under oxygen-enriched combustion and air combustion conditions. The experimental results showed that the generation of CO was 887 ppm under oxygen-enriched combustion, which was higher than that of 301 ppm under air combustion, and the generation of NO and SO2 were 247 ppm and 71 ppm, which were lower than that of 291 ppm and 100 ppm under air combustion, respectively. Secondly, the effects of different oxygen concentrations on the pollutant emission characteristics of sludge under oxygen-enriched combustion were investigated in this paper. Secondly, the article further investigated the effects of different oxygen concentrations on the emission characteristics of pollutants during oxygen-enriched combustion. The results showed that under the oxygen-enriched combustion condition, the generation of CO showed a tendency of decreasing and then increasing. The lowest CO generation was 631 ppm at 50% oxygen concentration, while the NO and SO2 generation showed a gradual increase at 50% oxygen concentration, with 283 ppm and 79 ppm, respectively; however, in the range of 21% to 50% oxygen concentration, the growth of NO and SO2 generation was significantly lower than that in the range of 50% to 100% oxygen concentration. The growth trend in the range of 50% to 100% oxygen concentration is significantly lower. In summary, oxygen-enriched combustion in an atmosphere with 50 per cent oxygen concentration is more conducive to suppressing the generation of combustion pollutants.

1. Introduction

Municipal wastewater treatment plants produce a large amount of sludge while purifying water bodies. Sludge has a complex composition and contains a large amount of organic matter, pathogens, heavy metals, and persistent organic pollutants that are difficult to degrade, which, if improperly disposed of, can cause serious secondary pollution of the water body, soil, and atmospheric environment[1-2]. Currently, the mainstream sludge disposal methods include incineration, anaerobic fermentation, aerobic composting, and pyrolytic carbonisation[3-5]. The traditional incineration technology has some drawbacks. About 79% of the nitrogen in the combustion air does not participate in the reaction, but needs to be heated and discharged with the flue gas, resulting in low system thermal efficiency, high flue gas treatment load, high NOX generation, and low CO_2 concentration in the flue gas, which is not conducive to subsequent carbon capture and sequestration/utilisation[6]. Oxygen-enriched combustion technology provides a new idea to solve the above difficulties[7]. Introducing this technology into the field of sludge disposal not only inherits all the advantages of incineration technology, but also achieves the synergies of energy efficiency improvement, pollution reduction and resource recovery through technological upgrading, which promotes the sustainable development of cities and environmental protection[8-9].

Magdziarz et al.[10] investigated the combustion and pyrolysis characteristics of different sludges and found that increasing the O_2 concentration was favourable to promote sludge combustion. Jin et al.[11] investigated the effects of O_2 concentration and other factors on the oxygen-enriched combustion characteristics of sludge and NO_X emission characteristics. The study showed that, when the O_2 concentration was constant, the rate of diffusion of O_2 was lower in O_2/CO_2 atmosphere than it was in O_2/N_2 atmosphere. The combustion rate and burnout characteristics of sludge particles in O_2/CO_2 atmosphere were weaker than their combustion in O_2/N_2 atmosphere, and the conversion rate of fuel nitrogen in O_2/CO_2 atmosphere was lower than that in O_2/N_2 combustion atmosphere with the same O_2 concentration. With the increase of O_2 concentration, the oxygen-enriched combustion characteristics of sludge particles were significantly improved, but resulted in higher NOx

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emission and fuel nitrogen conversion.Zhou et al.[12] analysed and compared the effect of O_2 concentration on sludge combustion characteristic parameters, and the results showed that increasing the O_2 concentration decreased the ignition temperature and the burnout temperature, significantly increased the overall combustion index, and improved the sludge combustion characteristics.

This paper focuses on the pollutant emission characteristics of sludge under oxygen-enriched combustion and air combustion conditions, and the pollutant emission characteristics of sludge under different oxygen-enriched conditions.

2. Experimental

2.1. Experimental Materials

Sludge was sourced from a wastewater treatment plant. Ten sampling points were evenly distributed within the sedimentation tank for sludge collection. The retrieved sludge underwent natural air-drying for one week. Dry sludge with a particle size of 100 µm–150 µm was selected for further drying until mass remained constant after three consecutive weighings. The prepared sludge underwent analysis, with results presented in Table 1 and subsequently, quantitative trace element characterisation via X-ray fluorescence spectroscopy was conducted, with findings detailed in Table 2.

Table 1 Industrial analysis and elemental analysis of sludge.

Industrial analysis (wt.%)				
C^a	H^a	O^a	N^a	S^a
26.33	4.56	15.59	4.84	0.87
Elemental analysis (wt.%)				Q_b(MJ/kg)
Volatile matter	Fixed carbon	Ash content	Moisture	
48.12	4.07	44.31	3.50	9.70

[a]AR: Received Basis
[b]LHV: Lower Heating Value

Table 2 Analysis of other elements in sludge.

wt.%	SiO_2	P_2O_5	Al_2O_3	Fe_2O_3	SO_3
ppm	28.91	10.02	7.28	4.94	3.04
wt.%	CaO	K_2O	MgO	TiO_2	Na_2O
ppm	2.87	2.44	1.63	0.58	0.42
wt.%	Sr	Cr	Zr	Rb	Pb
ppm	148.00	114.00	113.00	48.00	27.00
wt.%	As	Ni	Zn	Cu	
ppm	21.00	8.00	0.32	0.01	

The prepared sludge samples were pelletised. Weigh 0.6 g of sludge sample, pour it into the mould, put the mould into the tablet press (Type HY-12, Tianjin Tianguang Optics Instrument Co.,Ltd.), and the pressure of the tablet press was kept at 2.5±0.1 MPa for each pelleting, and the pelleting was completed with sludge particles as a cylinder with a diameter of 10 mm at the bottom and a height of 10 mm.

2.2. Experimental platform and operating conditions

The prepared sludge samples were pelletised. Weigh 0.6 g of sludge sample, pour it into the mould, put the mould into the tablet press (Type HY-12, Tianjin Tianguang Optics Instrument Co.,Ltd.), and the pressure of the tablet press was kept at 2.5±0.1 MPa for each pelleting, and the pelleting was completed with sludge particles as a cylinder with a diameter of 10 mm at the bottom and a height of 10 mm.

The sludge oxygen-enriched combustion system is shown in Figure 1. This experimental bench consists of four parts, which are gas supply system, feeding system, sludge combustion furnace system and exhaust gas detection system.

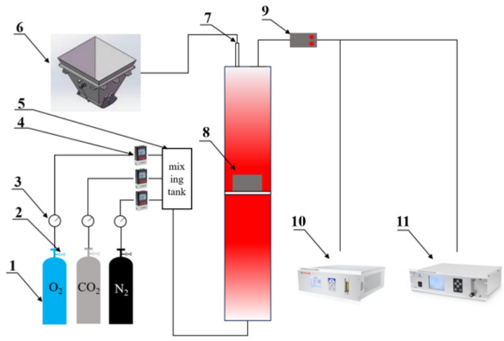

Figure 1 The sludge oxygen-enriched combustion system gas source (1), shut-off valve (2), pressure reducing valve/gauge (3), mass flow meter (4), gas mixing tank (5), silo (6), feeder (7), the sludge burner system (8), filter (9), on-line infrared gas analyser (10), on-line infrared flue gas analyser (11)

2.2.1 Gas supply system

The gas supply system is mainly used to configure the combustion atmosphere required by the sludge oxygen-enriched combustion system. It consists of gas source (1), shut-off valve (2), pressure reducing valve/gauge (3), mass flow meter (4), gas mixing tank (5) and so on. The gas source consists of oxygen, carbon dioxide and nitrogen cylinders, which are connected to a special mass flow meter (4) after being depressurised to 0.4 MPa through a pressure reducing valve (2) and then entering the gas mixing tank for full mixing before entering the sludge combustion system. The mass flow meter can accurately control the experimental gas flow rate with an accuracy of 0.01L, realising air combustion and oxygen-enriched combustion atmospheres for sludge at different oxygen concentrations.

2.2.2 Feeding system

The feeding system consists of a silo (6) and a feeder (7). The sludge particles in the silo can be pushed into the sludge burner system (8) in a precise continuous or intermittent manner by adjusting the motor.

2.2.3 Sludge combustion furnace system

The sludge burning furnace system (8) adopts three temperature zones high temperature tube furnace BTF-1600C-III. The system consists of three digital temperature controllers which can control the temperature independently and can set up 30 sections of rising and falling temperature programmes, and the heating zones are all heated by Super-1800 grade silicon molybdenum rods. The technical parameters are shown in Table 3.

Table 3 Technical parameters of horizontal tube furnaces

Rated power	13KW
Rated Voltage	AC 208-240V Single Phase, 50/60 Hz
Maximum temperature	1600°C for 1 hour
Continuous working temperature	≤1550°C
Recommended heating rate (β)	≤1200°C, β≤50°C/min; 1200°C-1500°C, β≤5°C/min; ≥1500°C, β≤2°C/min
Furnace tube size	High-purity corundum tube Φ80*1200mm
Length of heating zone	760mm
Length of constant temperature zone	400mm
Temperature control precision	±1°C
Heating element	Silicon molybdenum rod
Thermocouple	type B
Number of temperature zones and temperature control	Three temperature zones have three independent temperature control systems, 518P temperature controller, PID automatic temperature control system, intelligent 30-segment programmable control, built-in overheating protection and thermocouple failure alarm, default DB9 PC communication port.
Number of silicon molybdenum rods	4 rods in temperature zone 1, 4 rods in temperature zone 2, 4 rods in temperature zone 3, totalling 12 U-shaped silicon molybdenum rods.
Dimension	1400×580×800mm (combustion furnace)
Net weight	300KG

2.2.4 Exhaust gas detection system

The exhaust gas detection system consists of a filter (9), an on-line infrared gas analyser (10) and an on-line infrared flue gas analyser (11). The filter is used to filter impurities such as fly ash particles in the flue gas. The on-line infrared gas analyser is Gasboard-3100 produced by Hubei Cubic-Ruiyi Instrument Co., Ltd. and the on-line infrared flue gas analyser is Gasboard-3000plus produced by Hubei Cubic-Ruiyi Instrument Co., Ltd.

2.2.5 Experimental method for the sludge oxygen-enriched combustion system

The sludge oxygen-enriched combustion system was used for the experiments. Through the air combustion and oxygen-enriched combustion conditions, to clarify the impact of oxygen-enriched combustion of pollutant generation and emission characteristics; by changing the combustion conditions, to study the impact of oxygen-enriched combustion conditions on the pollutant generation characteristics, to find the best sludge oxygen-enriched combustion conditions.

(1) Study the characteristics of pollutant generation under air combustion and oxygen-enriched combustion conditions as follows: a. Inject inert nitrogen and check the airtightness of the experimental device using the soap bubble method to prevent experimental errors; b. Inject the experimental atmosphere (air atmosphere: 21% O_2+79% N_2; oxygen-enriched atmosphere: 21% O_2+79% CO_2), with a primary air excess coefficient of α=0.1, and use a flow meter to The oxygen, nitrogen and carbon dioxide flow rates were calibrated respectively to ensure the stability and accuracy of the combustion atmosphere; c. After the equipment was stabilised, the warming procedure of the sludge combustion furnace system was set to heat up the reaction system at a rate of β=50 °C/min and maintain it at 800 °C while keeping the experimental atmosphere blowing; d. After the temperature of the sludge combustion furnace system was stabilised, 2 kg of sludge particles were weighed and placed into a silo. The sludge particles were pushed into the combustion furnace by a propeller. Use online infrared flue gas analyser and online infrared gas analyser to detect the concentration of pollutants and gas concentration, respectively, to be online infrared gas analyser detected CO, CH_4 concentration signal is less than 10 ppm when the sludge is considered to have been burned out, to stop this group of experiments.

(2) Study the effect of sludge oxygen-enriched combustion oxygen concentration on the characteristics of pollutant generation, the specific operation method is as follows: a. Pass inert nitrogen and use the soap bubble method to check the airtightness of the experimental device, to prevent experimental errors; b. Pass in the experimental atmosphere (21% O_2 and 79% CO_2, 30% O_2 and 70% CO_2, 50% O_2 and 50% CO_2, 70% O_2 and 30% CO_2, 100%O_2), the primary air excess coefficient is set to α=0.1, and the flow meter is used to calibrate the oxygen and carbon dioxide flow rate respectively to ensure the stability and accuracy of the combustion atmosphere; c. After the equipment is stabilized, set up the heating procedure of the sludge combustion furnace system, and heat up the reaction system and maintain it at 800 °C at a rate of β=50 °C/min respectively, while keeping the experimental atmosphere purged; d . After the temperature of the sludge combustion furnace system was stabilised, 2 kg of sludge particles were weighed and placed in a silo, and the sludge particles were pushed into the combustion furnace by means of a propeller. The online infrared flue gas analyser and online infrared gas analyser were used to detect the concentration of pollutants and gas concentration respectively, and when the online infrared gas analyser detected that the signal of CO and CH_4 concentration was less than 10 ppm, it was considered that the sludge was burned out, and this group of experiments was stopped.

3. Results and Discussion

3.1. Effect of Atmosphere on CO Emission Characteristics

Figure 2 illustrates CO generation characteristics under different combustion atmospheres. Comparative analysis reveals that CO concentration from sludge combustion under 21% oxygen enrichment conditions reached 887 ppm, substantially exceeding the 301 ppm observed under 21% oxygen air combustion conditions. During air combustion, the carbon matrix within sludge reacts exclusively with O_2 in the combustion environment for oxidation. However, diffusion resistance of O_2 towards sludge particles and the complex internal pore structure of sludge particles impede O_2 penetration into the particle interior. This results in partial anoxic conditions on the particle surface and within certain internal regions.

Under these conditions, the carbon matrix within the sludge undergoes both complete oxidation reactions and partial oxidation reactions, yielding CO_2 and CO respectively. Assuming the proportion of complete oxidation reactions is denoted as x, the corresponding chemical reaction is expressed as Equation (1). In an oxygen-enriched atmosphere, the carbon matrix in the sludge undergoes heterogeneous reactions with O_2 and CO_2 present in the combustion environment. The reaction between the carbonaceous matrix and O_2 within the sludge resembles that under air combustion conditions, but the presence of CO_2 alters the source of CO during combustion. Due to the high concentration and abundance of CO_2 in the enriched oxygen combustion environment, it gradually diffuses to react with the carbonaceous matrix within the sludge particles via gasification (Equation 2), thereby increasing the concentration of CO produced.

In conventional air combustion, although some CO_2 is produced during the combustion reaction, its concentration in the flue gas remains low. The contribution of the carbon matrix gasification reaction is negligible and is typically disregarded. However, during oxygen-enriched combustion, the significant changes in the combustion atmosphere and mode inevitably alter the role played by the gasification reaction in the combustion process. Secondly, as the gasification reaction between CO_2 and the carbon matrix is endothermic, it lowers the combustion reaction temperature of the sludge. This promotes both the incomplete oxidation reaction between the carbon matrix and O_2 and the gasification reaction between the carbon matrix and CO_2, significantly increasing the concentration of CO produced. Finally, the elevated CO_2 concentration in flue gas under oxygen-enriched combustion conditions inhibits the complete oxidation of the carbon substrate, further contributing to increased CO concentrations. Consequently, when the combustion atmosphere transitions from air combustion to oxygen-enriched combustion, the concentration of CO produced during sludge combustion increases significantly.

$$C+(1+x)/2O_2 \rightarrow xCO_2+(1-x)CO,\ \Delta H=-(123.5+285.5x)kJ/mol/C \quad (1)$$

$$C+CO_2 \rightarrow 2CO, \Delta H=-172kJ/mol/C \quad (2)$$

Additionally, Figure 2 demonstrates that CO generation exhibits distinct trends across varying O_2 concentrations. Within the 21%–50% O_2 range, CO production decreases as oxygen concentration increases—falling from 887 ppm at 21% O_2 to 631 ppm at 50% O_2 concentration, representing a 28.86% decrease and indicating a noticeable improvement in combustion conditions. This occurs because, with constant feed rate, increased oxygen content in the air supply enhances the complete oxidation reaction between the carbon matrix in the sludgeand O_2, leading to greater combustion efficiency. Consequently, most of the carbon matrixreacts with O_2 to produce CO_2. Simultaneously, the increased O_2 concentration accelerates the combustion rate of the sludge, elevating the surface temperature of the sludge particles and further promoting the complete oxidation reaction of the carbon matrix. When the O_2 concentration rises from 50% to 70%, the CO_2 concentration accelerated the combustion rate of the sludge, raising the surface temperature of the sludge particles and further promoting the complete oxidation reaction of the carbonaceous matrix. When the O_2 concentration increased from 50% to 100%, CO emissions did not decrease with the increase in oxygen concentration but instead showed an increasing trend. The CO production increased from 631 ppm to 1081 ppm, representing a 1.7-fold increase in CO emissions. Observations during the experiment revealed that when the O_2 concentration reached 70%, the sludge underwent rapid and violent combustion within the furnace chamber, even exhibiting flash combustion.

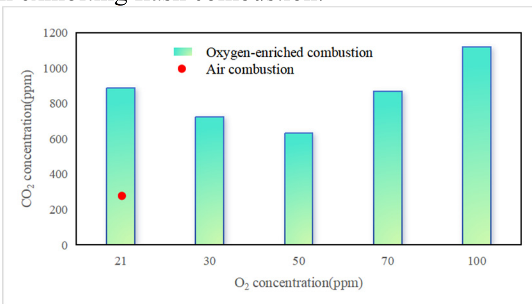

Figure 2 Characteristics of CO formation under different combustion atmospheres.

Therefore, this study concludes that beyond an O_2 concentration of 50%, the sludge combustion reaction rate continues to accelerate. This forms thin layers of CO_2 and CO near the sludge particle surfaces, impeding the diffusion of O_2 towards the sludge particle surface and resulting in a temporary lack of oxygen around the particle reaction zone. Concurrently, the occurrence of flash combustion deteriorates combustion conditions, thereby increasing CO emissions. This creates a temporary oxygen deficiency around the particle reaction zone. Concurrently, the occurrence of detonation worsens combustion conditions, thereby increasing CO emissions. As shown in the figure 2, within the O_2 concentration range of 70% to 100%, CO emissions even exceeded those observed at a 21% O_2 concentration.

3.2. Effect of Atmosphere on NO Emission Characteristics

Figure 3 illustrates NO formation characteristics under different combustion atmospheres. Comparison reveals that NO production under 21%O_2 enriched combustion conditions (247 ppm) is significantly lower than under 21% O_2 air combustion conditions (291 ppm), with a reduction exceeding 15%. This indicates that the enriched combustion atmosphere suppresses NO formation. Typically, NOx emissions during fuel combustion originate from thermal NOx, rapid NOx, and fuel NOx. Thermal NOx forms through the oxidation of N_2 in combustion air at elevated temperatures, with its generation rate and temperature following the Arrhenius law. That is, as temperature increases, the NOx formation rate rises exponentially. Rapid NOx is rapidly generated during fuel combustion when the fuel concentration is excessively rich. It is believed that NO formation involves hydrocarbons and nitrogen molecules, wherein fuel-derived carbonyl groups react with N_2 to produce CN compounds. Subsequently, N or CN collides with oxygen atoms, undergoing further oxidation to form NO. Fuel-type NOx arises when nitrogen atoms in fuel combine with various hydrocarbons to form cyclic or chain-like nitrogen compounds. During combustion, these nitrogen compounds oxidise to form NOx, termed fuel-type NOx. Typically, when fuel combusts in air at flame temperatures exceeding 1500°C, a portion of atmospheric nitrogen is converted into thermal NOx. As previously noted, CO_2 presence inhibits sludge combustion reactions. Consequently, under oxygen-enriched combustion conditions, lower fuel temperatures result in negligible thermal NOx formation, thereby reducing overall NO production. High concentrations of CO_2indirectly influence NOx-related chemical reactions by affecting the total amount of O/H chemical groups and the OH/H ratio, rather than directly acting on nitrogen-containing groups. Through the reaction

$$CO_2 + H \rightarrow CO + OH \tag{3}$$

Competes with the main chain reaction during combustion for H. The total amount of chain carrier H and O decreases, the OH/H ratio increases, and CO production also increases in the reaction zone. Taking the oxidation of NH_3 as an example, high CO concentrations promote the reaction between NH_2 and CO to form HNCO. However, due to the reduction in the number of O/H radicals, the reaction forming HNO.

$$NH_2 + O \rightarrow HNO + H \tag{4}$$

and the formation of NH

$$NH_2 + H \rightarrow NH + H_2 \tag{5}$$

Suppressed, thereby reducing NO formation. Furthermore, HCN is another primary gaseous product alongside ammonia during sludge volatilisation analysis. The reduction in chain carriers caused by CO_2 similarly impedes HCN oxidation. Compared to air combustion conditions, the lower HCN combustion rate in a CO_2 atmosphere is accompanied by higher CO and HNCO concentrations. Higher CO_2 concentrations diminish the proportion of oxidised HCN converted to NO, resulting in lower NO production under oxygen-enriched combustion conditions than under air conditions[5].

As shown in Figure 3, NO production gradually increases with rising O_2 concentration. Within the 21–50% O_2 range, the increase is relatively slow, rising from 247 ppm to 283 ppm (15.57% increase). However, within the 50–70% O_2 range, NO production increases rapidly, surging from 283 ppm to 514 ppm (an 81.63% increase). As oxygen content rises, the coke reaction accelerates, causing NO production to increase rapidly. Concurrently, elevated oxygen concentrations lower the ignition temperature of sludge particles, enhance overall combustion efficiency, reduce combustible gas concentrations in the combustion environment, and inhibit NO reduction reactions. Concurrently, elevated oxygen concentrations lower the ignition temperature of sludge particles, enhancing overall combustion efficiency and reducing combustible gas concentrations within the combustion environment. This diminishes conditions favourable for NO reduction reactions, whereas higher O_2 partial pressures promote oxidation of NO precursors, yielding increased NO formation. Moreover, elevated O_2 concentration implies reduced CO_2 concentration, diminishing CO_2's inhibitory effect on NO formation. Consequently, NO production increases more gradually within the 21%-50% O_2 concentration range, whereas it rises more rapidly between 50%-70%O_2.

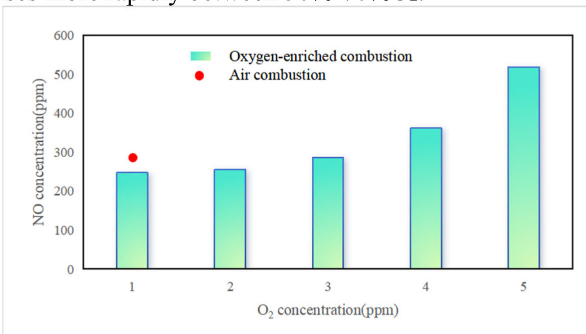

Figure 3 Characteristics of NO formation under different combustion atmospheres.

3.3. Effect of Atmosphere on SO_2 Emission Characteristics

Figure 4 illustrates the SO_2 generation characteristics of sludge under different combustion atmospheres. The figure 4 indicates that at 21% O_2concentration, the SO_2 generated during air combustion of sludgeis 100 ppm, significantly higher than the SO_2 generation (71 ppm) under 21% O_2 enrichment combustion conditions. This represents approximately 1.41 times the amount under oxygen-enriched combustion conditions. The primary forms of sulphur in sludge are organic sulphur and inorganic sulphur. Among these, organic sulphur is mainly present as mercaptans and sulphides. The primary forms of sulphur present in sludge are organic sulphur and inorganic sulphur. Organic sulphur primarily consists of mercaptans, sulphides, and phenols, while inorganic sulphur mainly includes $FeSO_4$, FeS_2, $CaSO_4$, and others. During air combustion, organic sulphur and sulphur from FeS_2 undergo thermal decomposition, releasing gaseous sulphur that is subsequently oxidised to form SO_2. Typically, sulphur in sludge is predominantly converted to SO_2, with SO_3 constituting a minor proportion. When the combustion atmosphere shifts from air to oxygen-enriched conditions, certain regions within sludge particles experience a weakly reducing environment, leading to the reduction of some sulphur to elemental sulphur. Additionally, under oxygen-enriched conditions, sludge combustion behaviour is less vigorous than in air combustion, suppressing sulphur release. Unreleased sulphur may react with abundant alkali and alkaline earth metals in the sludge to form sulphates without release. Notably, calcium sulphate formed from reactions with Ca remains in the ash, thereby reducing the amount of SO_2 generated[6].

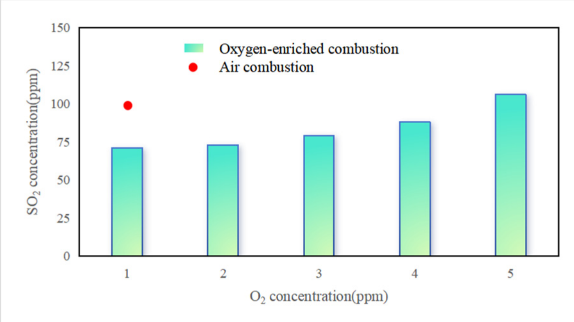

Figure 4 Characteristics of SO_2 formation under different combustion atmospheres.

As the O_2 concentration increases, the formation of SO_2 also rises. This is primarily due to the elevated O_2 concentration not only raising combustion temperatures but also promoting the release of inorganic sulphur. Analysis reveals that when the O_2 concentration increases from 21% to 50%, the SO_2 formation rises from 71 ppm to 79 ppm, representing a relatively small increase. When the O_2 concentration increased from 50% to 100%,the SO_2 production rose from 79 ppm to 106 ppm, representing a more substantial increase. Although the trend in SO_2 production with O_2 concentration mirrors that of NO, the underlying causes differ. At low O_2 concentrations, the combustion environment contains higher levels of CO_2 content in the combustion environment is high, leading to greater reduction of sulphur in the sludge combustion process into elemental sulphur and compounds such as COS. This results in lower SO_2 emissions. However, as the O_2 concentration increases, the oxidative environment intensifies. Sulphur released in the form of elemental sulphur and COS is re-oxidised to form SO_2, causing an increase in SO_2 production.

4. Conclusions

Experiments investigated pollutant formation under oxygen-enriched combustion versus air combustion conditions. Results indicate higher CO formation under oxygen-enriched conditions, while NO and SO_2 formation are markedly lower. Further experiments examined pollutant formation at varying oxygen concentrations during oxygen-enriched combustion. Findings show CO formation initially increases then decreases with oxygen concentration, reaching minimum levels at 50%. NO and SO_2 production increased with rising oxygen concentration, though the rate of increase was relatively slow within the 21%-50% O_2 range. Consequently, oxygen-enriched combustion at 50% oxygen concentration proved more effective in suppressing combustion pollutant formation.

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