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Experimental investigation of gasification and incineration characteristics of dried sewage sludge in a circulating fluidized bed

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HIGHLIGHTS

- Proposing a method of dried sewage sludge gasification and incineration.
- Analyzing the gasification process of dried sewage sludge in the CFB.
- Investigating the combustion characteristics of syngas and residues.
- Exploring the nitrogen transformation mechanisms in the system.

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ABSTRACT

Sewage sludge is noted for its high nitrogen content compared to most other fuels. A combined gasification and incineration process for the disposal of dried sewage sludge was tested in a pilot-scale circulating fluidized bed (CFB) gasifier and a down-flow combustor (DFC). Syngas produced from the CFB gasifier, together with fine solids, was pneumatically transported into the DFC for incineration in order to recover the heating value of the syngas with low nitrogen oxides emission. Measured data indicated that under typical operating conditions, approximately 90% of fuel-N was released into the gas phase and further reduced to N_2 in the gasifier. The NOx concentrations measured in the subsequent incineration process were 220 ± 6 mg/N m^3 (corrected to 6 vol% free O_2) due to effective air staging scheme that maintained the temperature in the DFC below 1150 °C. The conversion of fuel-N to NOx was found to be 1 ± 0.04%, based on elemental mass balance. The combustible content in the fly ash collected from the DFC was 2.8%, corresponding to an overall combustion efficiency of 99.2% in the system. The experimental results demonstrated that the two-stage process developed in the present study is very promising for environmentally friendly disposal of sewage sludge.

1. Introduction

With the continuous development of the economy and industry in China [1], the production of municipal sewage sludge has reached up to 4.0 million tons in 2010 and it will be expected to rise up to 6.0 million tons in 2020. In Europe, the total amount is expected to 13.0 million tons in 2020 [2]. However, the municipal sewage sludge formed during wastewater treatment contains undesirable components, including organic, inorganic and toxic substances, as well as pathogenic or disease-causing micro-organisms [3–5]. It is a critical issue to dispose the sewage sludge and to reduce air pollutions and contamination of soil and water resources.

Until now, there are numerous technologies to dispose the sewage sludge, i.e. land filling, recycling as fertilizer, dumping in the sea and incineration. Among those methods, incineration is the most attractive disposal route with the advantages of volume reduction, stabilization and harmlessness [6,7]. Figure in Refs. [8,9] shows that the incineration process consumed 24% of the sewage sludge produced in Denmark, 25% in the USA and 55% in Japan.

At present, the dominant furnaces for sewage sludge incineration are fluidized bed and multiple hearth furnaces (MHF). Other furnaces, including rotary kiln, cyclone and different types of smelting furnaces are also used [10,11]. It is well known that the nitrogen content of sewage sludge (4–9%) is considerably higher than that of other fuels, such as coal (0.5–1.5%) and biomass (0.3–1%) [12,13]. The emissions of NO_x and N_2O are anticipated to be high using conventional fluidized bed combustion, MHF or

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smelting technology. Previous studies [10,14] show that high concentrations of NO_x (600–900 mg/N m^3) are released due to high nitrogen contents in the sewage sludge. It is a critical issue to control nitrogen oxides emission for sewage sludge incineration.

For the purpose to control NO_x emission for sewage sludge incineration, a new method for sewage sludge incineration in two-stage was proposed. Firstly, dried sewage sludge was gasified in the CFB with 20–40% of the stoichiometric air. Secondly, the syngas and residues, with the temperature of nearly 800 °C, were pneumatically transported into the DFC to incinerate. The formation route of the fuel-N to NO_x can be excellently controlled and a lower NO_x emission can be expected with the two-stage method. To test the proposed two-stage method, a bench-scale rig was built and typical experiments were carried out. Process characteristics for the gasification and incineration process are investigated and key process parameters including NO_x emission and temperature are measured and analyzed.

2. Experimental

2.1. Experimental set-up

Fig. 1 shows a schematic diagram of the two-stage combined gasification and incineration system, consisting of a CFB gasifier, a down-flow combustor and auxiliary system.

The CFB riser is 90 mm in diameter and 1500 mm high. The feeding port is located at 240 mm above the air distributor. The primary air, which accounted for 20–40% of the stoichiometric air requirement, was supplied from the bottom of the gasifier as both fluidizing and gasifying agent. A hydrogen- and CO-rich syngas was produced in the CFB gasifier. Most solid particles (residues) were separated by the cyclone and returned to the bed through a U-valve, while fine particles escaping the cyclone were carried over by the syngas flow into the down-flow combustor. A 500 mm long, 48-mm ID horizontal pipe connects the cyclone outlet to the top of the DFC.

The particle-laden syngas flows into the DFC, 3 m high and 0.26 m in diameter, through a nozzle shown in Fig. 2. Air supply to the DFC was staged to optimize performance. The secondary air was supplied from the top, while the tertiary air was introduced at a position 600 mm below the nozzle to ensure complete combustion. A reducing zone was created between the secondary and tertiary air ports in order to reduce NOx formation.

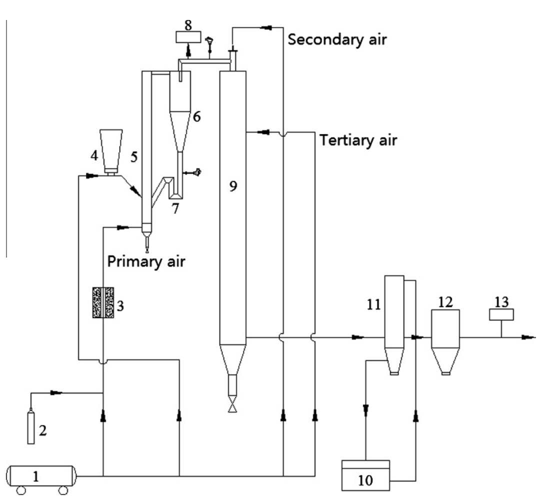

Fig. 1. Schematic diagram of the test rig. 1. Air compressor, 2. liquefied petroleum gas, 3. electricity heater, 4. screw feeder, 5. riser, 6. cyclone, 7. U-valve, 8. sampling port, 9. DFC, 10. water tank, 11. water cooler, 12. bag filter, 13. gas analyzer.

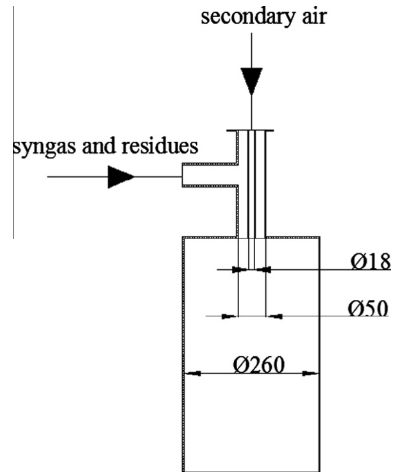

Fig. 2. The structure of the nozzle.

Five Ni–Cr/Ni–Si thermocouples in the CFB and five Pt/Pt–Rh thermocouples in the DFC are used to measure the temperature. Sampling ports are designed as follows. (1) The port at the outlet of the CFB is for syngas and residues. (2) The port at the outlet of a bag filter is for sampling fly ash. (3) Five ports located at 100, 400, 1400, 2400, and 3000 mm along the DFC below the nozzle are for flue gas. All the gas samples along the DFC are dried and filtered before entering individual analyzers. The syngas generated from the CFB is measured by a MAIHAK S710 analyzer with an accuracy of ±2%, and other gases generated from the DFC, including NO, NO_2, N_2O, CO, CO_2, H_2O, NH_3 and HCN, are measured by a Gasmet FTIR DX-4000 analyzer with an accuracy of ±2% in volume concentration. The O_2 concentration along the DFC is measured by the KM9106 with an accuracy of ±0.1% in volume concentration.

2.2. Dried sewage sludge characteristics

Dried sewage sludge from China was used in the experiments. The size range of dried sewage sludge is 0.6–1.8 mm. The d_{50} is 1.5 mm. The size distribution of dried sewage sludge is given in Fig. 3.

Table 1 lists the proximate and ultimate analysis results. As seen in Table 1, the water content of dried sewage sludge is 4.5% (95.5% dry matter), meaning a total dehydration happened. As a result, the lower heating value (LHV) of dried sewage sludge is 15.04 MJ/kg, equivalent to that of lignite (11.7–15.8 MJ/kg). The nitrogen content is 7.1%, obviously much higher than that of other fuels [12,13,24,25]. Table 1 also shows the volatile content is

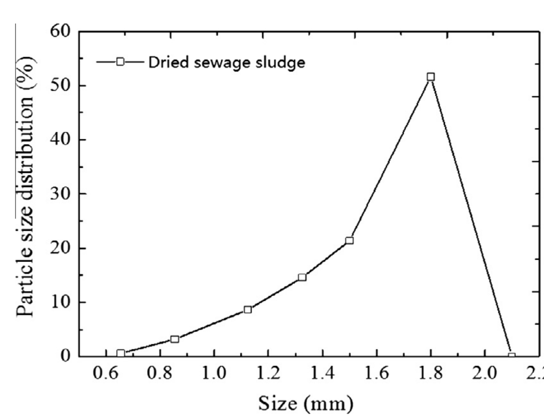

Fig. 3. Size distribution of the dried sewage sludge.