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RESEARCH ARTICLE

Incineration experiment of medical waste of novel coronavirus pneumonia (COVID-19) in a mobile animal carcass incinerator

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Abstract
Incineration experiment of medical waste was carried out in a mobile animal carcass incinerator. Simulated medical waste (69% cotton, 1.5% wood product, 4.5% mask and 25% moisture) was used as raw material. The temperature trend of first and second combustion chamber, the operating conditions and the emission characteristics of gaseous pollutants were studied. The results indicated that the temperature of first combustion chamber can be maintained at 550–650 °C without external heating, while in the final stage a burner was used to realize the burnout of material. The temperature of the second combustion chamber was always lower than that of the first combustion after the burner stopped working. The concentration of CO emission in flue gas was high due to the low disposal efficiency of the mobile incinerator, while NO_X and SO_2 emission concentrations were far below the standard limit value (GB 18484-2001).

Keywords Medical waste · Incineration · Temperature fluctuation · Furnace condition · Gaseous pollutants emission

Introduction

Medical waste is defined as the infectious waste generated by hospitals, health and epidemic prevention units, patient nursing homes, and medical research units [1]. According to data from the National health commission [2], in recent years, the amount of medical waste generated in China has been increasing year by year, from 550,000 tons in 2014 to 820,000 tons in 2019. At the end of 2019, the novel coronavirus pneumonia (COVID-19) caused a significant increase in the amount of medical waste produced, which is expected to increase by more than 25% in 2020. Medical waste is extremely infectious, biologically toxic and corrosive. If not handled properly, it will cause water, air and soil pollution and direct harm to humans, and even become the source of epidemics.

Medical waste is a heterogeneous multi-component mixture. Unlike single waste which has specific internal structure and external characteristics, the composition of medical waste is related to where it is generated and how it is collected and stored, which leads to large fluctuations in the characteristics of medical waste [3–7]. At present, there are already various methods for medical waste disposal; according to the different disposal processes, the medical waste disposal methods mainly include incineration, pyrolysis, chemical disinfection, high-pressure steam sterilization, plasma disinfection, sanitary landfill, electromagnetic wave disinfection, etc. [8–13]. Among them, the incineration method has the characteristics of complete disinfection and sterilization, and obviously volume reduction; which has become the most widely used medical waste treatment method in the world today [14–17].

Despite the above-mentioned advantages of incineration disposal methods, secondary pollutants may be generated during disposal, including SO_2, NO_X, particulate matter, HCl, heavy metals, dioxins, Polycyclic Aromatic Hydrocarbons (PAHs), etc. [18–23]. Alvim-Ferraz's study [24] showed that the emission of CO, SO_2 and HCl exceed the legal limit, while the concentration of NO_X was within the limit. Xie's result [9] showed that the emission of fine particles, CO, SO_2, NO_X and HCl were below the limits of Chinese standard, which means the pollutant emissions may not be a very serious problem when the incinerator operated

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in good conditions. Thompson [25] studied the heavy metal content of ash from a medical waste incinerator, and the result showed that the burned plastic wastes were a source of Pb. Krivanek [26] found that the Hg emission from some medical waste incinerators in US did not meet national standards. Duan's research [27] found that the distribution proportion of the mercury content in exhaust gas from medical waste was 34.0%. Mao's study [28] showed that the main heavy metal in medical waste was Zn. Dioxin is also one of the main pollutants produced by incineration of medical waste [29, 30]. Wang's research [31] found that the chlorine content of medical waste has an important impact on dioxin emissions, and the increased chlorine content will lead to more dioxins. Some studies show that the CO and HCl content also have an impact on the formation of dioxins [32, 33]. Lee [34] studied the influencing factors of PAHs generation and the results showed that the large amount of plastic in the medical waste caused the generation of PAHs to increase significantly. Singh's research [35] found the emission of PAHs was directly affected by incineration temperature. Meanwhile, Xie's experimental result [36–39] showed that the furnace temperature and the combustion method had a significant impact on the emission of pollutants.

At the beginning of this year, due to the outbreak of novel coronavirus pneumonia (COVID-19), the production of medical waste increased sharply and the disposal capacity of medical waste was seriously insufficient. In this research, we use mobile incinerators to treat medical waste as a backup medical disposal resource in case of emergency. Compared with the fixed medical waste treatment, the advantages of mobile incinerator are that it can realize the on-site disposal of medical waste and avoid the pollution leakage in the transportation link. The purpose of this experiment is to study the feasibility of using a mobile animal carcass incinerator to dispose medical waste, to obtain the operation characteristics and emission data, and supporting the subsequent development of mobile medical waste incinerator. The experiment was carried out in a mobile animal carcass incinerator, and simulated medical waste was used as raw material. The temperature of first and second combustion chamber were recorded every minute, and the emission concentrations of O_2, CO, NO_X and SO_2 were measured on-line.

Experimental section

Materials

Medical waste is a kind of heterogeneous and multi-component mixture. It does not have a specific internal structure and external characteristics like a single substance, and its physical properties vary with the change of the proportion and nature of the components. Due to the real medical waste is dangerous and difficult to obtain, in this experiment we used simulated medical waste (SMW), which is mainly used to simulate the medical waste produced by the novel coronavirus pneumonia (COVID-19). The proximate and ultimate analysis data of SMW is given in Table 1, and the SMW consists of 69% cotton, 1.5% wood product, 25% moisture and 4.5% mask (all from our employees) in mass percent.

It can be seen that the fixed carbon, ash and moisture content of cotton and mask are very low, and lots of volatiles will be produced at high temperature. For wooden products, in addition to volatiles, it also contains a certain amount of moisture and fixed carbon. At the same time, it can be seen that the heat values of these kinds of medical waste are very high, which means they are suitable for incineration disposal.

Experimental equipment

The experiment was performed in a mobile animal carcass incinerator, as shown in Fig. 1, and the schematic diagram of the equipment is shown in Fig. 2. The equipment mainly includes the following parts: first combustion chamber, second combustion chamber, air cool, quench cooler + cyclone separation, and folding chimney. Eight diesel burners (single power 260 kW) were equipped in the first combustion chamber to ignite the waste materials, and another diesel burner was installed at the entrance of the second combustion chamber to increase the temperature of the second combustion chamber. Air cooler was used for the initial cooling of high temperature flue gas, and the quench cooler + cyclone separation was used to realize the flue gas cooling and fly ash removal. After that, the cooled flue gas was discharged through the folding chimney.

Table 1 Proximate and ultimate analysis for materials

Content	M_{ar}/(%)	A_{ar}/(%)	V_{ar}/(%)	FC_{ar}/(%)	$Q_{ar,net}$/(kj/kg)	C_{ar}/(%)	H_{ar}/(%)	O_{ar}/(%)	N_{ar}/(%)	S_{ar}/(%)
Cotton	2.3	0.18	96.74	0.78	18,799	51.64	5.74	39.91	0.18	0.05
Wooden product	14.83	2.94	69.41	12.82	15,856	40.32	4.68	0.18	0.06	36.99
Mask	0.46	0.19	98.49	0.86	41,402	86.48	11.64	1.05	0.00	0.18
Simulated medical waste	26.83	0.18	72.22	0.77	14,507	40.13	4.56	27.59	0.13	0.6

ar as received basis

Fig. 1 Mobile animal carcass incinerator

The infrared high temperature thermometerused to measure the temperature in this test is ML5-4SCU (reytek company, USA). Gaseous pollutants emission in flue gas was merely measured online by flue gas analyzer (MG5+, QZTC company, German) at the outlet of air cooler.

Experimental matrix

The mobile animal carcass incinerator was operated in batch processing mode; the disposal process includes feeding, incineration, cooling and slag removal. For each batch, the disposal time is about 90 min and the treatment capacity is nearly 150–200 kg/h. Therefore, in this experiment 200 kg SMW was used for the incineration experiment. The experiment started at 15:00 and lasted 90 min in total. The experimental process is as follows:

1. At 15:00, the loading work was completed, and the experiment was ready to begin. In this experiment, the SMW was fed by artificial. There is a door at the rear of the car that can be opened horizontally. Before the start of the experiment, all SMW was sent into the first combustion chamber using trolleys and shovels.
2. At 15:01, the burner in the second combustion chamber started, and the heating of the second combustion chamber began.
3. At 15:11, the temperature of the second combustion chamber reached 530 °C. Eight burners in the first combustion chamber started, and the induced draft fan started at the same time. The air volume for the induced draft fan was 9360 m^3/h. And the residence time for flue gas in the second combustion chamber was nearly 1 s.
4. At 15:15, 8 burners in the first combustion chamber stopped.
5. At 15:18, the burner in the second combustion chamber stopped.
6. At 15:38, due to the temperature of the first combustion chamber was too low, the amount of air supplied to the first combustion chamber was reduced by shutting down the air supply fan. At the same time, the cooling fan of the air cooler was turned off.
7. At 16:16, one burner in the first combustion chamber started.
8. At 16:30, the experiment was over.

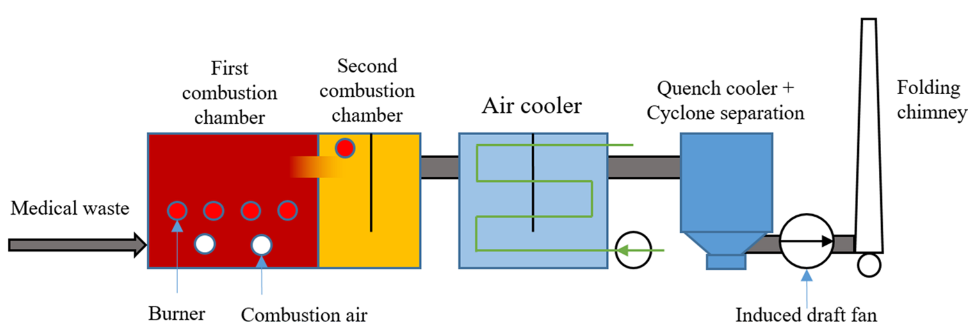
Results and discussion

Temperature trend

First combustion chamber

The temperature trend of the first combustion chamber during the experiment is shown in Fig. 3. At the beginning (0–10 min), the temperature of the first combustion chamber remained constant, which means the temperature increase of the second combustion chamber had no impact on the first combustion and the thermal insulation between the two chambers was good. 11 min after the start of the experiment, due to eight burners in the first combustion chamber started to work, the temperature rapidly increased to 864 °C at the 15th minute, and then eight burners were stopped. After that (15–38 min), the temperature generally showed a downward trend, and there were some fluctuations mainly due to the instability of the material burning. At the 38th

Fig. 2 Disposal process diagram of mobile animal carcass incinerator



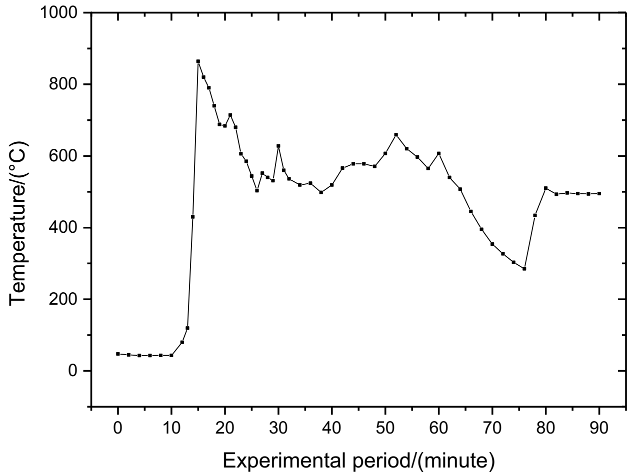


Fig. 3 Temperature of first combustion chamber

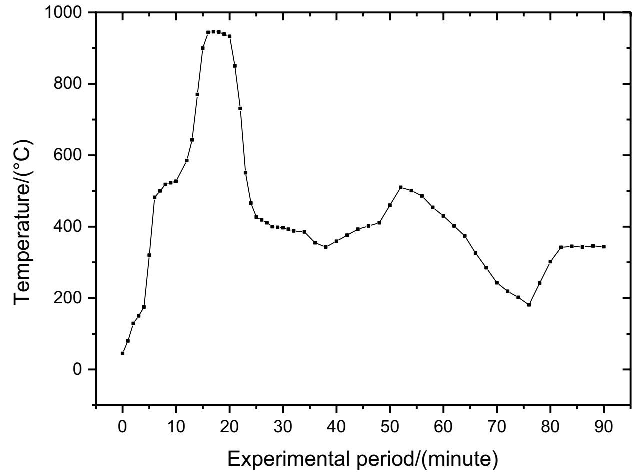


Fig. 4 Temperature of second combustion chamber

minute, due to the amount of air supplied to the first combustion chamber was reduced, the decrease in heat dissipation and the increase in the temperature of combustion area caused the temperature of chamber a briefly rise, while it began to decline at the 52nd minute mainly due to the lack of remaining materials. At the 76th min, the temperature drops to 285 °C; to realize the burnout of materials, one burner in the first combustion chamber started to maintain the temperature of 500 °C until the end of the experiment. From the experimental results, it can be seen that under this experimental condition, after the eight burners were closed the temperature of the first combustion chamber can be maintained at 550–650 °C by self-combustion of materials; however, to achieve the burnout of the materials in the later stage of disposal, at least one burner is required to maintain the temperature of the chamber.

Second combustion chamber

The temperature trend of the second combustion chamber during the experiment is shown in Fig. 4. At the first minute, the burner in the second combustion chamber started and the heating of the second combustion chamber began. During 8–10th min, the rate of temperature rise in the second combustion chamber decreased significantly which was mainly limited by the power of the burner. At the 11th minute, due to eight burners in the first combustion chamber started to work, the temperature of the second combustion chamber also increased to 946 °C at the 17th min, and then the burner in the second combustion chamber was stopped. After that (18–38th min), the temperature of the second combustion chamber continued to drop. Due to the air supply was reduced at the 38th minute, the temperature of the second combustion chamber also increased firstly and then declined. At the later stage of disposal (after the 76th min), due to the heat provided by the burner in the first combustion chamber, the temperature in the second combustion chamber was maintained at nearly 350 °C.

From the experimental results of the temperature in the second combustion chamber, it can be seen that after the burner in the second combustion chamber stopped, the temperature of the second combustion chamber was always lower than that of the first combustion chamber. This phenomenon can be explained by the following two reasons. First, the heat dissipation problem of the second combustion chamber was serious; this can be proved by the last experimental process (after the 76th min), the temperature of the second combustion chamber was 150 °C lower than that of the first combustion chamber. Second, since the second combustion chamber has no air inlet, the air supplied for combustion was basically sent through the inlet of the first combustion chamber; this leads to the result that combustion was the main reaction in the first combustion chamber, while the proportion of gasification reactions was very low.

Furnace condition

O_2 content

The O_2 content in flue gas at the outlet of air cooler is shown in Fig. 5. At the beginning of the experiment (0–18th min), due to the combustion of diesel in the burner and the unstable ignition and burning process of materials, the O_2 content in flue gas was not stable and went through a period of significant decline and rise. After that (18–38th min), the O_2 content in flue gas was basically stable between 14%–15%. At the 38th minute, due to the amount of air supplied to the first combustion chamber was reduced, the O_2 content in flue gas decreased obviously first; after the 60th minute, the O_2 content in flue gas rebounded which is mainly due to the

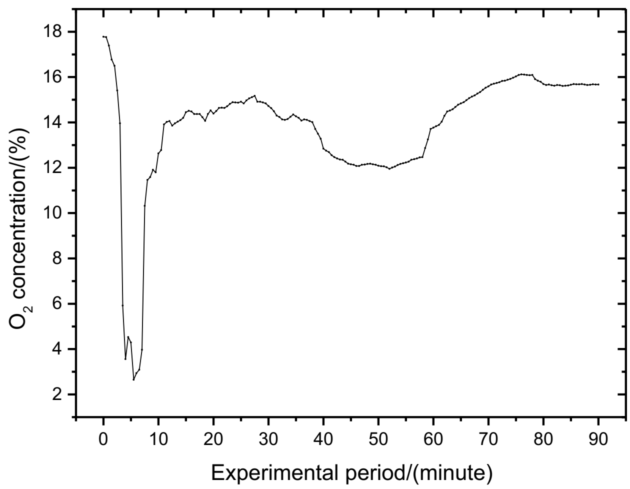


Fig. 5 O_2 content in flue gas before quench cooler

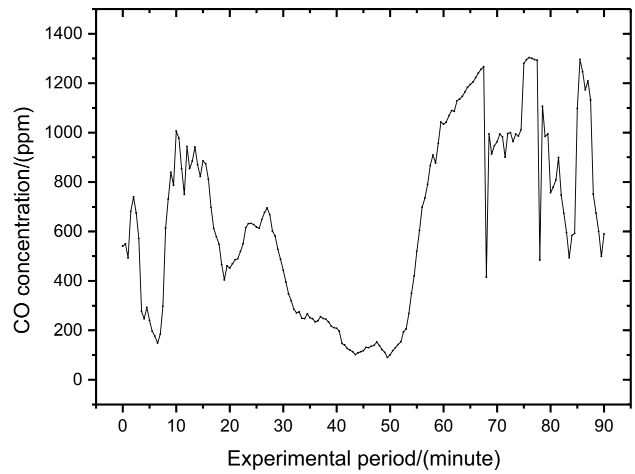


Fig. 6 CO concentration in flue gas

decrease of residual fuel material. At the burnout process (after the 76th min), the O_2 content in flue gas was basically maintained at about 15.5%. It can be seen from the experimental results that due to the limited adjustment methods, during the whole experiment process the O_2 content in flue gas remained at a high level; as a result, the first combustion chamber was always in a state of combustion, and the proportion of gasification reactions in the first combustion chamber was very low.

CO content

According to the Pollution Control Standard for Hazardous Waste Incineration (GB 18484-2001), the concentration of CO in flue gas is converted to 11% oxygen condition and the result is shown in Fig. 6. At the beginning of the experiment (0–18th min), due to the combustion of diesel in the burner and the unstable ignition and burning process of materials, the CO concentration in flue gas fluctuated greatly; the maximum value reached 1006 ppm, while the minimum value was 149 ppm. After that, during the stable combustion process (18–38th min) the CO concentration was at a relatively low value (average 446 ppm). At the 38th minute, with the decrease of air supply the CO concentration first decreased slightly and then increased significantly; during 40–50th min, the decrease of CO was mainly due to the increase of temperature in the first combustion chamber and the subsequent improvement of combustion condition. While during 50–68th min, the decrease of combustion temperature and the insufficient combustion of residual materials lead to the significant increase of CO emission (maximum value 1267 ppm). At the burnout process (after the 76th min), due to the operation of the diesel burner, there were some fluctuations of CO emission.

From the whole experimental process, the CO emission concentration was relatively high, the average value of CO from 18th–75th (without diesel combustion) was 560.6 ppm which far exceeded the National standard limit (<100 ppm, GB 18484-2001). It is because compared with the fixed large-scale incineration treatment device, the mobile incinerator has a smaller furnace volume, a simple air supply system, and a single operation mode, which results in a poor effective disposal than fixed treatment device.

Gaseous pollutants emission

During the experiment, the concentrations of NO_X and SO_2 in flue gas were measured online (every 5 s) by flue gas analyzer (MG5 +, QZTC company) at the outlet of air cooler. According to the Pollution Control Standard for Hazardous Waste Incineration (GB 18484-2001), the concentrations of NO_X and SO_2 in flue gas were converted to 11% oxygen condition and the data is shown in Table 2. During the experiment, the maximum concentrations of NO_X and SO_2 were 205.3 and 71.4 mg/m^3, respectively. At the same time, their emission concentrations showed great fluctuation. The minimum value of NO_X was 9.5 mg/m^3, and the average value was close to 100 mg/m^3; while for SO_2, the minimum value was only 1.1 mg/m^3, and the average value was close to 20 mg/m^3. Compared with the limit value stipulated in

Table 2 Gaseous pollutants emission compared with National standard

Emission	Maximum	Minimum	Average	National standard
NO_X (mg/m^3)	205.3	9.5	99.7	500
SO_2 (mg/m^3)	71.4	1.1	19.5	400

the national standard GB 18484-2001, the emission concentrations of NO_X and SO_2 were far below the standard limit, which means that the emissions of NO_X and SO_2 in the medical waste incinerator are not major problem.

Conclusions

According to the results of the incineration experiment of medical waste in the mobile animal carcass incinerator, the following conclusions can be drawn:

1. During this experiment, the temperature of the first combustion chamber and the second combustion chamber both showed fluctuation trends. The temperature of the first combustion can be maintained at 550–650 °C by self-combustion of the medical waste, and the burner in the second combustion chamber needs to be kept normally open to maintain the temperature of the second combustion chamber above 850 °C to achieve the burnout of material. In the final stage, to achieve the burnout of medical waste, at least one burner is need in the first combustion chamber to maintain combustion condition. The main reaction in the first combustion chamber was combustion reaction, while the proportion of gasification reaction was very low. The temperature of the second combustion chamber was always lower than that of the first combustion after the burner turned off.
2. During this experiment, the O_2 content in flue gas was always at a high level, and this leads to the phenomenon that the first combustion chamber was always in a state of combustion. By adjusting the air supply volume, the temperature of the first combustion chamber can be controlled at a high level. The average concentration of CO emission from 18th–75th (without diesel combustion) was 560.6 ppm, which is a relatively high value, mainly due to the low disposal efficiency of the mobile incinerator.
3. During this experiment, the concentrations of NO_X and SO_2 showed great fluctuated within a certain range. Compared with the limit value stipulated in the national standard GB 18484-2001, the emission concentrations of NO_X and SO_2 meet the standards throughout the experiment, which means the emissions of NO_X and SO_2 may not be a serious problem in the medical waste incinerator.
4. Based on the test results, we find that the following three aspects need to be improved for the development of the new type medical waste mobile incinerator. Firstly, the air supply range of the first combustion chamber needs to be expanded; by adjusting the air supply, the condition of the first combustion chamber should be able to change between combustion and pyrolysis conditions. In this way, the first combustion chamber is kept in the combustion state during the start-up and burnout stages, and it can be transformed into pyrolysis state in the stable stage. Thus, the emission of gaseous pollutants will be significantly reduced. Secondly, the volume of the second combustion chamber should be increased. It ensures that the residence time of high temperature flue gas (temperature above 850 °C) can reach more than 2 s to achieve complete decomposition of organic pollutants. Thirdly, the flue gas purification system is needed. Since the emission of NO_x and SO_2 is very low, the flue gas purification system should mainly include quenching, alkali washing and bag dedusting to control the emission of HCl and dioxin.

Compliance with ethical standards

Conflict of interests All of the authors declare no conflicts of interest.

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