Drying Characteristics and Odor Concentration in Tail Gas in Vacuum Drying of Municipal Sewage Sludge

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Abstract—As one of the most common solid wastes, municipal sewage sludge needs to be dried before its disposal and resource reuse. In this study, the effects of vacuum degree, heat source temperature and sludge thickness on drying rate and odor concentration in tail gas were studied through orthogonal experiments carried out on the lab-scale vacuum heat-conductive sludge drying device; The effects of heat source temperature on drying rate and odor concentration in tail gas were studied through comparative experiments of atmospheric state and vacuum state (-0.08MPa). The results show that the sludge thickness is the main factor affecting the sludge static drying rate, and the vacuum degree is the main factor affecting the odor concentration in the tail gas of sludge static drying. Under vacuum state (-0.08MPa), sludge can be dried efficiently while using low-grade heat source. In addition, while maintaining a high drying rate, the odor concentration in the tail gas will also be significantly reduced by reducing the generation of volatile sulphur compounds (VSCs).

1. Introduction

Municipal sewage sludge is one of the common solid wastes in modern human daily life. It is a mixture of organic and inorganic substances and contains various pollutant components.

Due to the rapid growth of population and the rapid improvement of industrialization, how to effectively dispose and resource reuse municipal sewage sludge has become a problem that the whole world has to face[1]. Conventional disposal methods for municipal sewage sludge are incineration, landfill and agriculture[2]. In recent years, resource reuse methods, such as the recovery of sludge resources in bio-refinery systems, have also been gradually explored[3]. However, the moisture content of municipal sewage sludge is still about 80% after mechanical dewatering, so for subsequent disposal and resource reuse, the sludge needs to be further dried[4, 5].

Nowadays, the main drying methods of sludge are convective drying, heat conductive drying and solar drying, but they are usually carried out under atmospheric state[6]. As a new drying methods, vacuum drying has been proven to be an effective way of sludge drying [7]. However, there is a lack of information about sludge vacuum drying, especially the drying characteristics and odor concentration in tail gas in vacuum drying of municipal sewage sludge.

In the present work, a lab-scale heat-conductive sludge vacuum drying device was used to reveal the effects of vacuum degree, heat source temperature, and sludge thickness on sludge vacuum drying characteristics and odor concentration in tail gas. Meanwhile, a pilot sludge vacuum drying device was used to verify the feasibility of sludge vacuum drying technology, and reveal the superiority of vacuum drying compared with atmospheric drying in terms of drying characteristics and odor concentration in tail gas.

2. Materials and Methods

2.1. Lab-scale heat-conductive sludge vacuum drying device

The sewage sludge samples after mechanical dewatering were collected from a municipal wastewater treatment plant in Nanjing, China. The initial moisture content was 80.6±1.1% (w.b.).

A set of three-factor and four-level orthogonal experiments was designed to investigate the effects of vacuum degree, heat source temperature and sludge thickness on sludge drying characteristics and odor concentration in tail gas. The orthogonal experiments were carried out on a lab-scale vacuum heat-conductive sludge drying device, as shown in Figure 1.

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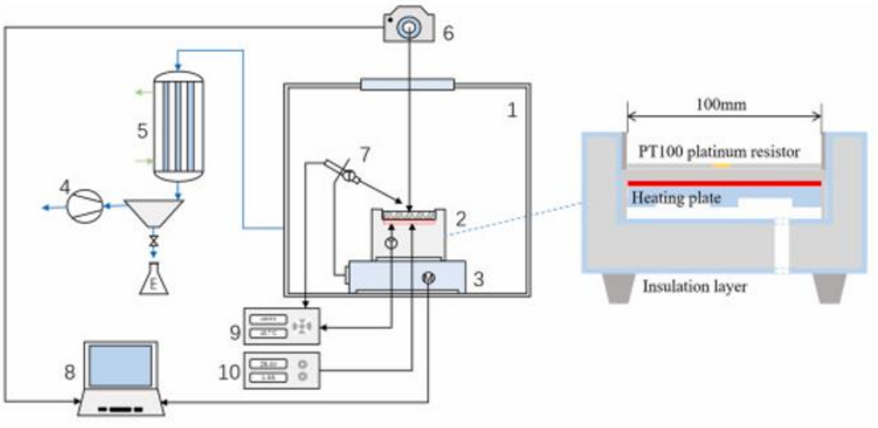


1.Vacuum chamber;2. heater;3. electronic balance;4. vacuum pump;5. condenser;6. camera;
7. infrared thermometer;8. computer;9. temperature recorder;10. DC power supply

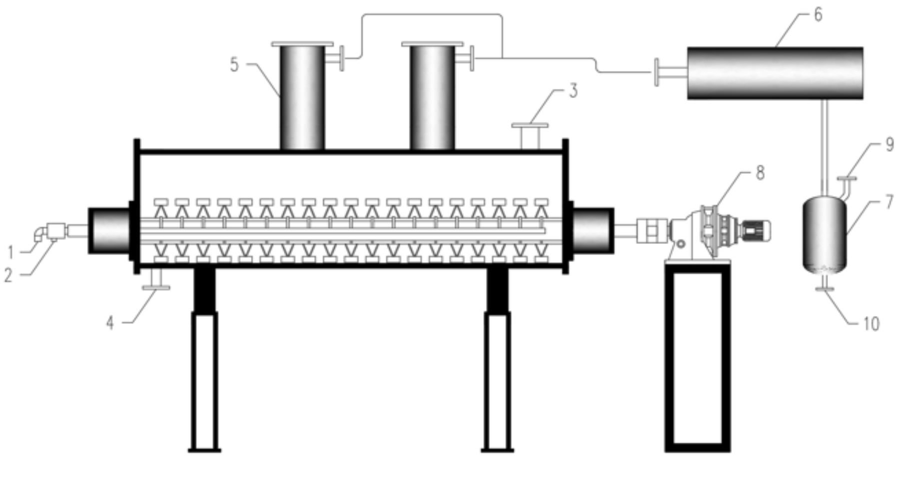
Fig.1 Schematic diagram of lab-scale vacuum heat-conductive sludge drying device

The sludge was evenly spread on the heater. When the heater was preheated to the target temperature, the vacuum pump started to work until the target vacuum degree was reached. The electronic balance recorded the total mass of heater and sludge every 20 seconds. The heater kept heating until the dry basis moisture content of the sludge was lower than 0.1g·g^{-1}. -0.02, -0.04, -0.06, and -0.08 MPa were selected as the vacuum degree. 80, 100, 120, and 140 °C were selected as the heat source temperature. 3.4, 6.8, 10.2, and 13.6 mm (the weights of the sludge were 30, 60, 90, and 120 g) were selected as the sludge thickness.

2.2. Pilot continuous sludge vacuum drying device

The sewage sludge samples after mechanical dewatering were collected from a municipal wasterwater treatment plant in Longyan, China. The initial moisture content was 80.2±1.3% (w.b.).

A set of comparative experiments were designed to investigate the effect of heat source temperature on sludge drying characteristics and odor concentration in tail gas under atmospheric state and vacuum state. The comparative experiments were carried out on a pilot continuous sludge vacuum drying device, as shown in Figure 2.



1.Heat source inlet;2. heat source outlet;3. sludge inlet;4. sludge outlet;5. bag-type dust collector;6. condenser;7. condensate water collector;8. reduction motor;
9. vacuum pump connection;10. condensate water outlet.

Fig.2 Schematic diagram of pilot continuous sludge vacuum drying device

The thermal conductive oil heated to the target temperature entered the heat source inlet through the circulation pump, so that the device obtained a stable heat source temperature. Meanwhile, the vacuum pump started to work until the target vacuum degree was reached. -0.08 MPa was selected as the vacuum degree of the vacuum state. 80, 90, 100, 110, and 120 ℃ were selected as the heat source temperature.

3. Results and Discussions

3.1. Lab-scale orthogonal experiments

The detailed experimental programs and experimental results of the orthogonal experiment are presented in Table 1.

Table 1**.** Scheme of the orthogonal experiments

No.	Factors (A, B and C)			Results	
	Vacuum degree (MPa)	Heat source temperature (°C)	Sludge thickness (mm)	Drying rate ($g\cdot g^{-1}\cdot min^{-1}$)	Odor concentration
1	1(-0.02)	1(80)	2(6.8)	0.0126	4169
2	1	2(100)	1(3.4)	0.0468	3090
3	1	3(120)	4(13.6)	0.0098	3090
4	1	4(140)	3(10.2)	0.0202	1738
5	2(-0.04)	1	3	0.0081	4169
6	2	2	4	0.0075	5495
7	2	3	1	0.0363	4169
8	2	4	2	0.0341	3090
9	3(-0.06)	1	4	0.0047	3090
10	3	2	3	0.0092	1738
11	3	3	2	0.0236	1320
12	3	4	1	0.0444	980
13	4(-0.08)	1	1	0.0378	2317
14	4	2	2	0.0176	1320
15	4	3	3	0.0115	1738
16	4	4	4	0.0078	1320

Table 2**.** Range analysis of the experimental results of drying rate

Item	Factors (A, B and C)		
	Vacuum degree (MPa)	Heat source temperature (°C)	Sludge thickness (mm)
K_1 avg	0.0224	0.0158	0.0413
K_2 avg	0.0215	0.0203	0.0220
K_3 avg	0.0205	0.0203	0.0122
K_4 avg	0.0187	0.0266	0.0075
R	0.0037	0.0108	0.0339
The optimal levels	1(0.02)	4(140)	1(3.4)
The optimal combination		A1B4C1	
Order of influencing factors		C＞B＞A	

The range analysis of drying rate in Table 1 are shown in Table 2. From the results, in the lab-scale static vacuum drying process of municipal sludge, the influence of sludge thickness on drying rate was far greater than that of vacuum degree and heat source temperature. Meanwhile, as expected, the drying rate increased with the increase of heat source temperature and decreased with the increase of sludge thickness. However, the drying rate did not increase with the increase of vacuum degree, but showed a downward trend. This is because with the increase of vacuum degree, the sludge surface is prone to crusting, thus inhibiting the precipitation of water in the sludge[8].

Table 3**.** Range analysis of the experimental results of odor concentration

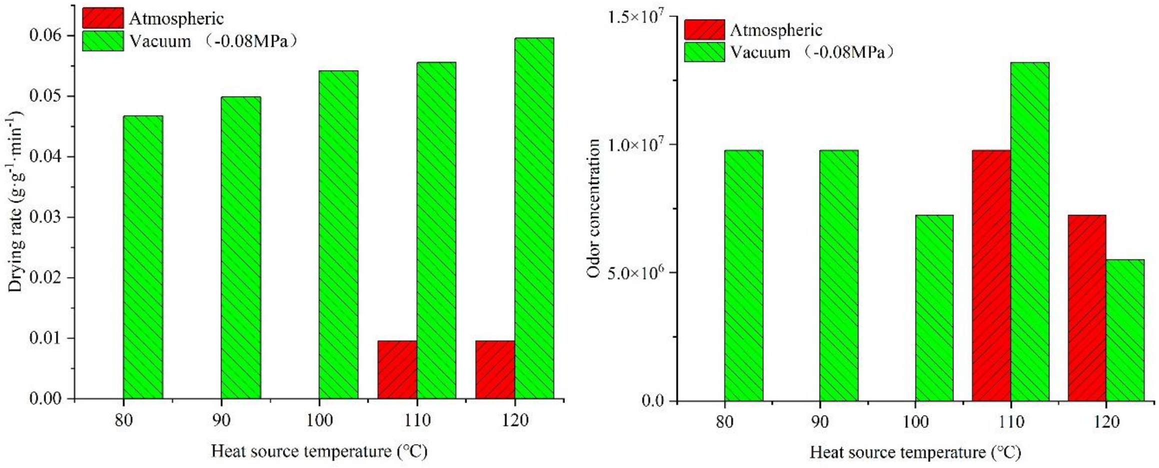
Item	Factors (A, B and C)		
	Vacuum degree (MPa)	Heat source temperature (°C)	Sludge thickness (mm)
K_1 avg	3021.75	3436.25	2639
K_2 avg	4230.75	2910.75	2474.75

K_3 avg	1782	2579.25	2345.75
K_4 avg	1673.75	1782	3248.75
R	2557	1654.25	903
The optimal levels	4(-0.08)	4(140)	3(10.2)
The optimal combination		A4B4C3	
Order of influencing factors		A＞B＞C	

The range analysis of odor concentration in Table 1 are shown in Table 3. From the results, in the lab-scale static vacuum drying process of municipal sludge, the influence of vacuum degree on odor concentration in tail gas was greater than that of heat source temperature and sludge thickness. With the increase of vacuum degree, the odor concentration in the tail gas decreases significantly.

3.2. Pilot comparative experiments

The results of the comparative experiment are shown in Figure 3. Particularly, when the heat source temperature is 80, 90, and 100 °C, the sludge hardly dried under atmospheric state, so these three conditions are no longer considered in the presentation and discussion of the results.



(a) Drying rate (b) Odor concentration in tail gas

Fig.3 Comparison of drying rate (a) and odor concentration in tail gas (b) under atmospheric and vacuum (-0.08MPa) state

Under vacuum state (-0.08MPa), the retention time of sludge in the pilot continuous sludge drying device is 55 mins, while under atmospheric state, this time is 160 mins. This is because under atmospheric state, the moisture content of sludge after drying by pilot drying device is still high, and the fluidity of sludge at this moisture content is very poor. However, under vacuum state (-0.08MPa), the sludge is in the form of small particles after drying by the pilot drying device, which leads to a significantly shorter retention time.

From Figure 3(a), under normal pressure, the drying rates of sludge at heat source temperatures of 110 and 120°C are 0.0095 and 0.0096 $g\cdot g^{-1}\cdot min^{-1}$, respectively. The drying rates of the same heat source temperature in vacuum state are 0.0555 and 0.0595 $g\cdot g^{-1}\cdot min^{-1}$, which are 5.84 times and 6.18 times of atmospheric state, respectively. This shows that when the heat source temperature is low and the sludge is difficult to dry under atmospheric state, the sludge can still be dried efficiently under vacuum state.

From Figure 3 (b), it can be found that the odor concentration in tail gas is generally too high whether under vacuum state (-0.08MPa) or under atmospheric state. This is because in the pilot continuous sludge drying device, continuous addition of wet sludge and discharge of dried sludge will lead to the peak drying rate of sludge, and the maximum flow of condenser in the device cannot meet the flow required for the condensing of the water vapor generated by sludge drying. Meanwhile, according to some previous studies, volatile sulphur compounds (VSCs) are the main cause of odor concentration in the tail gas of sludge drying[9-12]. Therefore, when collecting tail gas, a large number of sulphur compounds that should be condensed with the water vapor generated by sludge drying will be collected at the same time. However, even so, it is still possible to determine whether the sludge vacuum drying can effectively reduce the odor concentration in the tail gas by comparing the odor concentration under atmospheric and vacuum state (-0.08MPa). In the case that the drying rate is far higher than the atmospheric state, the vacuum state (-0.08MPa) has a similar odor concentration in the tail gas. This shows that when the drying rate is equal, the sludge will produce more sulphur compounds when drying under the atmospheric state, so that the odor concentration in its tail gas will be much higher than that under vacuum state.

When the heat source temperature is 110°C, the odor concentrations in the tail gas are 9.77×10^6 and 1.32×10^7

when the sludge is dried under normal pressure and vacuum, respectively, while the odor concentrations are 7.24 × 10^6 and 5.50 × 10^6 when the heat source temperature is 120°C. No matter in the air pressure state or the vacuum state, the odor concentration in the tail gas has decreased. This is because when the temperature of the heat source increases, the temperature of the water vapor generated by sludge drying also increases, making it easier to be condensed by the condenser and reducing the volatile sulphur compounds (VSCs) in the tail gas. Compared with atmospheric state, the decrease of the odor concentration is larger under vacuum state, which means that the sludge drying under vacuum state will release less sulphur compounds that cannot be condensed together with the water vapor.

4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) The results show that in the static vacuum drying of sludge, sludge thickness is the main factor affecting the drying rate, followed by heat source temperature, and vacuum degree is the main factor affecting the odor concentration in the tail gas.

(2) Vacuum drying of sludge can still achieve efficient drying of sludge when low-grade heat source is used.

(3) Vacuum drying of sludge can effectively reduce the generation of volatile sulphur compounds (VSCs) in the drying process, thus effectively reducing the odor concentration in the tail gas.

Acknowledgments

The supports from National Key Research and Development Program of China (2020YFC1908700) are gratefully acknowledged.

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