Influencing factors of the drying rate of sludge for solar drying chamber

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Abstract. In view of the problems of low solar energy utilization efficiency, drying efficiency to be improved and sludge adhesion in the process of solar drying sludge, the research was carried out on the heat collection effect of solar collectors, sludge drying characteristics and sludge drying process, as well as the influence of sludge drying process parameters on the sludge drying rate such as hot air temperature, solar radiation intensity and air substitution, on the self-built industrial simulation test bench. The results show that: the maximum temperature difference between the inside and the outdoor environment of the solar collectors is 36℃, when the outdoor environment temperature of the developed solar collectors is 13-26℃; the optimum process parameters of sludge drying rate under the experimental conditions that the moisture content of wet sludge is 82.7%, are as follows: the temperature of hot air is 43℃, the maximum solar radiation intensity (about 12:00), the optimal flow rate of air is controlled at 1.2m/s, the thickness of the material layer is 3cm, the large contact between air and materials improves the problem of sludge adhesion. All which provide a theoretical basis for the implementation on the industrialization of solar drying sludge.

1. Introduction

Municipal sludge has a large moisture content (the factory moisture content is about 80%) Which its components are diverse and complex [1]. There are multiple organic pollutants and multiple pathogenic microorganisms in it. These characteristics cause the landfill, composting and burning for the sludge to be difficult. Therefore, the sludge must be dried and dehydrated [2] in order to ensure the stability of the sludge composition. It is currently one of the most economical and energy-saving sludge drying methods to use solar energy for drying. In recent years, the solar drying device has been widely promoted and applied in Europe due to its convenient operation, simple structure, and low operating cost [3-4]. The development and utilization of solar energy is also in line with my country's strategic development direction of energy conservation and emission reduction because of the shortage of energy in our country.
Tianjin University and Tianjin Jizhuangzi Sewage Treatment Plant jointly conducted an experimental study on the use of solar drying technology to dry sludge in order to further reduce the operating cost of sludge dewatering. Zheng Zonghe et al. proved through experiments that the use of solar sludge drying technology to dewater sludge is a feasible new technology, which is energy-saving when applied to sludge dewatering in municipal sewage plants. Lei Haiyan et al. explored the feasibility of using hybrid solar dryers to dry sludge and the drying characteristics of sludge. Li Jiaxiang used plastic sheds and sunlight to dry sludge and organic waste, and initially designed a plastic shed with high temperature and low humidity to achieve the purpose of drying sludge and other organic matter quickly.

But so far, most solar sludge drying technologies have the problems of low solar energy utilization efficiency and low sludge drying efficiency, sludge formation and small scale of drying equipment. How to effectively improve the utilization efficiency of solar energy resources and form an efficient sludge drying process requires in-depth research and engineering demonstrations. This paper conducts in-depth research on the heat collection effect of solar collectors, sludge drying characteristics and solar drying sludge process, examines the heat collection effect of solar collectors and explores the sludge drying process parameters such as the temperature of hot air, solar radiation intensity, air velocity and material layer thickness et al. On the effect of sludge rate, gaining in a relatively complete sludge drying process as to lay a foundation for the comprehensive promotion of solar sludge drying technology.

2. Experimental materials and equipment

2.1. Experimental samples
The sludge used in this experiment is from the dehydration workshop of a sewage treatment plant. The moisture content of the received base was measured to be 82.7% in a paste form. According to the industrial analysis and elemental analysis standards of coal, the air drying base obtained about the physical and chemical parameters of sludge are shown in Table 1.

| Industrial analysis (%) | Element content (%) |
|-------------------------|---------------------|
| M<sub>ad</sub> | A<sub>ad</sub> | V<sub>ad</sub> | F<sub>ad</sub> | C<sub>ad</sub> | H<sub>ad</sub> | O<sub>ad</sub> | N<sub>ad</sub> | S<sub>ad</sub> |
| 5.00 | 62.00 | 29.70 | 3.30 | 22.4 | 4.7 | 66.6 | 5.6 | 0.7 |

2.2. Experimental device and method
The solar collector is composed of a heat absorbing body, a shell, a transparent cover plate, an insulator and related parts which is shown in Figure 1. Sunlight shines on the heat sink through the transparent cover, most of the solar radiation energy is absorbed by the absorber to be converted into heat energy and transferred to the air in the fluid channel. Then the air is heated, and the temperature gradually rises and flows out from the upper end of the outlet.

![Figure 1. Structural diagram of solar collector.](image-url)
This paper adopts a self-designed high-efficiency solar collector which its structure is: adopting a multi-space heat-absorbing body type heat collector, loosely stacked iron filings as a porous absorber spread between the glass transparent cover plate and the heat-absorbing bottom plate, The transparent cover plate used is made of ordinary flat glass, the heat preservation material is made of 50 mm polystyrene board, and the outer shell is made of aluminum alloy plate. The collector is placed at an angle of 45 degree, and the outer plane size of the solar collector is 2000 mm×1000 mm. The heat exchange area of the solar heat collector is relatively enlarged, and the heat exchange coefficient between the air and the heat absorption plate is increased, and the heat collection effect is improved.

2.3. Analysis of sludge drying characteristics
The device used in the sludge drying characteristics test is DHS16-A fast moisture analyzer. The weight reduction method is used to determine the change of material moisture content with time. Suppose the initial mass of sludge is $m_0$ (g); the mass at n minutes is $m_n$ (g), where $n=1, 2, 3...$; the mass of sludge after drying is $m_f$ (g); the time interval is $\Delta t$ (min ); The mass of absolute dry matter of sludge is $m_d$ (g). The calculation of the moisture content of the sludge sample during the drying process is shown in formula (1).

$$w = \frac{m_n - m_f}{m_n} \times 100\%$$  \hspace{2cm} (1)

Derivation of formula (1) is calculated to obtain the drying rate $N$ of the sludge in the drying process, as shown in formula (2).

$$N = \frac{dw}{dt} \times 100\%$$  \hspace{2cm} (2)

2.4. Industrial simulation test bench for solar drying of sludge
The process of solar drying of sludge is as follows: After the air is heated to above 50℃ in the solar collector, it is transported to the sludge drying bin by an induced draft fan to dry the sludge until the moisture content is less than 40%; If the hot air in the heater does not reach above 50℃, a gasification incinerator is added, and the hot air above 550℃ generated by the incineration of the sludge after drying is used to supplement the heat source of the drying chamber to maintain the efficient drying of the drying chamber.

3. Results and discussion

3.1. Research on the heat collection effect of solar collectors
With reference to the national standard “Test Methods for Thermal Performance of Solar Collectors”, the heat collection efficiency is studied on the self-developed solar collectors and the time selected for comparison experiments when the weather conditions are basically the same, the temperature inside the heat collector is measured under different outdoor ambient temperature conditions to calculate the maximum temperature difference between the inside of the heat collector and the outdoor environment, and the result is shown in Figure 2. When the outdoor environment temperature is -1-7℃, 9-20℃ and 13-26℃, the maximum temperature difference between the inside of the collector and the outdoor environment is 30℃, 34℃ and 36℃ respectively. The maximum temperature difference increases between the inside of the heat collector and the outdoor environment as the outdoor temperature increases, and the better the heat collection effect of the solar heat collector is.
3.2. Solar sludge drying test

The solar sludge drying test was carried out on the self-built solar drying sludge test bench. The test conditions are as follows: the moisture content of the wet sludge is 82.7%, the material layer thickness is 3cm, when it is different for temperature, air velocity and the thickness of the layer, the moisture content of the sludge is measured at regular intervals, and the law of the influence of these three factors on the drying rate of the sludge is obtained.

3.2.1 The influence of air temperature. This experiment was carried out in July, choosing a few days with roughly the same weather conditions (clear weather, the test time is 12:00-14:00 every day), and the air velocity of 1.0m/s to conduct a comparative test. The test results are shown in Figure 3. It can be seen from the figure that when the air flow rate and return ratio are constant, the higher the air temperature, the greater the drying rate of the sludge. The reason is that as the air temperature increases, the heat transfer coefficient between the air and the sludge increases. In the early stage of drying, the air temperature has a greater impact on the drying rate, but in the later stage, the effect is not significant. The reason is that the sludge drying rate is mainly to remove free water in the early stage, which is greatly affected by external conditions. But in the later what is removed is bound water, which is mainly related to the shape and structure of the sludge itself, and is less affected by...
external conditions. Therefore, in the actual industrial production of sludge, the air temperature used in the early stage should be higher, and the air temperature used in the later stage should be lower [5].

Figure 3. Effect of air temperature on drying rate.

Figure 4. Effect of air velocity on drying rate.

3.2.2 The influence of air velocity. The influence of air flow rate on drying rate is shown in Figure 4. It can be seen from the figure that as the air flow rate increases, the drying rate becomes larger; in the early stage of sludge drying, the free surface moisture is lost, at this time, the air flow rate has a greater impact on the drying rate; in the later stage of sludge drying, it is removed to the bound water inside the sludge, at the same time, the drying rate depends on the internal structure of the sludge, and the wind speed has little effect.

3.2.3 The contact condition of air and material. This test adopts the natural circulation form of air penetration through the mesh belt laying to observe the contact between air and materials when the air velocity is 1.0m/s and the test time is 12:00-14:00, the material layer thickness is 2cm, 3cm, and 4cm.

The airflow penetrates the material layer vertically. When the thickness of the material layer is 2cm, 3cm, the material can be evenly suspended in the airflow to obtain a very large gas-solid contact area, which enhances the heat and mass transfer between the airflow and the material and strengthens the drying process; When the material layer thickness is 4cm, the material cannot be evenly suspended in the air. After the test, the final moisture content of the materials with layer thicknesses of 2, 3, and 4 cm was measured by an infrared moisture meter, and the measured results were 79.5%, 80.3% and 81.2% respectively. Considering the drying effect and economy, the thickness of the material layer is set to 3cm, which not only ensures good contact between the air and the sludge during the drying process, but also increases the production scale and reduces costs.

3.2.4 The shape change of sludge during drying. Taking 10g of sludge with a moisture content of 82.7%, using the DHS16-A fast moisture analyser, setting the final heating temperature to 43℃, and conducting a sludge drying experiment. Automatically collecting and recording data every 30s to plot the sludge drying rate. The curve is shown in Figure 5.
Figure 5. Drying rate curve of sludge.

The whole drying process of sludge is divided into three stages according to the change of its shape, the apparent change of sludge during drying is shown in Figure 6.

(a) Crack development section      (b) Crack shrinkage section    (c) Overall shrinkage section

Figure 6. Apparent change of sludge during drying.

(1) Crack development section
In the experiment, it is observed that once the sludge begins to dry, tiny cracks will gradually appear on the surface which will gradually become larger as the drying progresses, this period of time appears as an approximately constant speed section at stage I in Figure 5. When the surface of the sludge is still wet, the cracks can appear in places with defects on the surface or low local moisture content because of having fast water loss in these two places, which cause local shrinkage of the sludge surface to produce cracks. The cracks cause the sludge to crack at the sludge cracks and in the vicinity of the cracks and the water to evaporate faster, and so the cracks become larger. However, the increase of the cracks has almost negligible effect on the drying rate of the sludge, and so the drying rate still shows a downward trend.

(2) Crack shrinkage section
In this stage, most of the surface moisture of the sludge is removed, and the internal moisture of the sludge is removed after many hard-shell cracks. This stage roughly corresponds to the slow-down drying section of the drying rate curve (stage II). With the release of water, the cracks that shrink and close will cause the adjacent cracks to increase. This process is very complicated, and the drying rate of the sludge shows a downward trend with a larger decline.

(3) Overall shrinking section
The overall shrinking section (stage III) is a short period of time before the end of drying. At this time, the sludge begins to shrink as a whole so that the cracks are reduced, and the small cracks are gathered. At this stage, the drying speed decreases sharply on the drying rate curve and then again
tends to flatten. In the dried sludge, there are many filamentous fibres between the small cracks, and some cracks only have these filamentous fibres. This is because the inside of the sludge shrinks and deforms. These filaments make the cracks close to adhere among each other.

4. Summary
On a self-designed solar collector test bench, it was studied on the heat collection effect under different climatic conditions, investigated to the influence of air temperature, solar radiation intensity, hot air flow rate, and material layer thickness on the drying rate of sludge. Analyzed on the shape changes of the sludge during the drying process. Experimental research found that with the increase of outdoor temperature, the maximum temperature difference between the inside of the collector and the outdoor environment increases, the better the heat collection effect of the solar collector; the best process parameters for the sludge drying rate under the test conditions are: The temperature of the hot air is 43℃, when the solar radiation intensity is the highest (about 12 noon), the best air flow rate is controlled at 1.0 m/s, the material layer thickness is 3cm, the air contact with the material has no dead angle and the contact surface area is maximized.

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