Drying Experiment and Drying Model Analysis of Dehydrated Sludge Particles

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Abstract. A sludge drying experiment was conducted with dehydrated sludge particles as the research object, and the effects of temperature and particle size on sludge drying characteristics were discussed. The results show that the average drying rate of sludge can be increased by increasing the drying temperature and decreasing particle size of sludge, that is, the drying process of dehydrated sludge particles is controlled by internal migration. According to Fick's second law, the simplified diffusion model of sludge drying is obtained by regression of experimental data, the simulation results obtained by the simplified diffusion model are in good agreement with the experimental results, which can well reflect the drying process of sludge particles and provide technical basis for the control of dehydrated sludge particles drying process.

1. Introduction

The sludge treatment methods mainly include landfill, incineration, and utilization of compost resources[1]. Drying is necessary for any utilization. Sludge has poor fluidity, strong adhesive force, difficult dispersion and, easy sticking and scarring during drying, in addition, resistance of moisture transfer in materials and unit energy consumption are high[2], so how to dry sludge economically and efficiently has become an important topic for sludge treatment. Sludge drying kinetics is to study the relationship between moisture content and various dominant factors during sludge drying process, which reflects the change law of heat and mass transfer indirectly from the macro and micro levels. The qualitative and quantitative study of the sludge drying kinetics has important theoretical and practical significance for scientifically setting the drying cycle, adjusting the drying process, improving the efficiency, reducing energy consumption, and developing and operating drying systems. The research on sludge drying kinetics is also an important basis for the research on sludge pretreatment methods.
At present, scholars at home and abroad have done a lot of research on sludge drying below 100℃. The researches on sludge drying kinetics are mainly based on the numerical simulation of drying process to obtain the drying equation, of which the thin-layer drying of sludge is the most widely studied\[^{[4-6]}\]. Based on the basic diffusion mass transfer theory, a semi-empirical model of the wet sludge drying had been obtained by using experimental data regression in a bubbling fluidized bed in the literature\[^{[7]}\], in this model, the diffusion coefficient was assumed to be constant in the experimental process. However, in the actual drying process, sludge particles will undergo morphological changes in the drying process, such as shrinkage and cracking, which will inevitably lead to changes in diffusion coefficient. Considering that sludge exists in the shape of particles in the traditional sludge drying process, in this paper, the diffusion coefficient was set as a function of time, all these factors were taken into account, and The experimental datas were regressed to obtain a simplified diffusion model for sludge drying, which predicts the variation rule of sludge moisture content with time under different drying temperatures and particle sizes, and provides technical basis for the control of its drying process.

2. Instruments and Materials

2.1. Experimental Materials

The sludge with a moisture content of about 80% were taken from the dewatering workshop of Everbright Water (Jinan) Co., Ltd., and made into spherical particles with a radius of 2-20mm, and dried at 80℃, 120℃ and 160℃, respectively.

2.2. Experimental Instruments and Methods

![Rapid Moisture Analyzer](image)

Figure 1. Rapid Moisture Analyzer

The experimental instrument is DHS16-A Rapid Moisture Analyzer (Shanghai Longtuo Instrument Equipment Co., Ltd.) as shown in Figure 1. The output parameters of the rapid moisture analyzer are the real-time weight of the sludge sample. Datas are collected every 1 minute during the test. The mass of sludge at n minutes is set to \(m_{tn}\) (n = 1, 2, 3 ... The unit is g), and the mass of the dry matter in the sludge is \(m_{ds}\). The real-time data of the moisture content of the sludge samples obtained in the test were processed by equation (1) and equation (2), and analyzed by Origin 9.1.

Wet-based moisture content of sludge samples during drying:
The drying rate is

\[ v_n = \frac{x_{n-1} - x_n}{\Delta t} \]  

3 Experimental Results

3.1 Influence of Drying Temperature on Drying Characteristics

The moisture content curve of Ф20mm sludge particles at different temperatures are shown in Figure 2. It can be seen from Figure 2 that as the drying temperature increase, the complete drying time of sludge particles decrease, when the temperature increases from 80°C to 120°C, the complete drying time of sludge particles are significantly shortened, while the temperature increases from 120°C to 160°C, the complete drying time of sludge particles are not shortened significantly. It is obvious that the drying rate can be increased by increasing drying temperature.

![Figure 2. Effect of Temperature on Moisture Content of Ф20mm Sludge Particles](image)

3.2 Effect of Sludge Particle Size on Drying Characteristics

![Figure 3. Effect of Different Particle Sizes on Moisture Content of Sludge Particles at 120°C](image)
The moisture precipitation curve of sludge particles with different particle sizes at 120°C are shown in Figure 3. It can be seen from Figure 3 that as the particle size increase, the complete drying time of sludge particles increase at the same temperature, there is not much difference between the complete drying time for Φ10mm and Φ6mm particles, and the complete drying time significantly increases at Φ18mm. It is obvious that the sludge drying process is controlled by internal migration, and the drying rate is determined by water diffusion rate.

4. Analysis of Drying Kinetics Model

4.1 Drying Model

The sludge drying rate is mainly affected by the water vapor diffusion rate, which can also be verified in many literatures [8-10]. The moisture content of sludge particles changes continuously with time, and the evaporation interface gradually migrates into the particles, so the diffusion belongs to non-steady-state diffusion. The Fick's second law is often used to solve the problem of non-steady-state diffusion. The factors that affect the moisture diffusion are all attributed to the effective diffusion coefficient, and the relationship between the change of the moisture with time and the local humidity gradient is established, as shown in Equation 3.

$$\frac{\partial X}{\partial t} = \nabla (D_{eff} \nabla X)$$  \hspace{1cm} (3)

In Equation 3, $X$ is the average dry basis moisture content of sludge particles (kg/kg), $D_{eff}$ is the effective diffusion coefficient.

The sludge particles used in the drying test are spherical. In order to solve the sludge moisture content at different times during the drying process, the following assumptions are made.

- The moisture content inside the sludge particles is uniform.
- There is no temperature gradient in the sludge particles.
- The conditions of the drying experiment is constant, which conclude the temperature and humidity of the drying medium and the contact between drying medium and sludge particles.

To facilitate calculation, the moisture content of sludge particles is dimensionless, as shown in Equation 4.

$$MR = \frac{X - X_e}{X_0 - X_e}$$  \hspace{1cm} (4)

In Equation 4, $MR$ is the relative moisture content, $X_0$ is the initial moisture content, $X_e$ is the equilibrium moisture content at the end of drying.

The quality of the material does not change at the end of drying. At this time, the moisture content of the material is in equilibrium with the surrounding humidity, so it is also called the equilibrium moisture content. This value is difficult to measure and is affected by ambient temperature and humidity. However, the moisture content of the material is usually very low after the heat drying is completed. So Equation 4 can be transformed to Equat 5.

$$MR = \frac{X}{X_0}$$  \hspace{1cm} (5)

Equation 3 can be transformed to Equation 6.
Equation 6 applies to the drying process of spherical materials with different initial and boundary conditions.

At the beginning of drying, the moisture of the sludge particles is not lost, and the initial moisture content is maintained, so the initial conditions are shown in equation 7.

\[ MR = 1 \quad (0 < r < R, t = 0) \] (7)

After the drying starts, the surface moisture is quickly lost. The boundary condition is shown in equation 8.

\[ MR = 0 \quad (r = 0, t > 0) \] (8)

During the drying process, sludge particles will undergo morphological changes, such as shrinkage and cracking, which will inevitably lead to changes in the diffusion coefficient. Therefore, the diffusion coefficient can be considered as a function of time, as shown in Equation 9.

\[ D_{eff} = D(t) = D_0 f(t) \] (9)

In Equation 9, \( D_0 \) is the constant term of the variable diffusion coefficient in m²/min, \( f(t) \) is the change term of the diffusion coefficient with time due to various factors.

For a single diffusion of spherical particles, Equation 6 can be transformed to Equation 10.

\[ \frac{\partial MR}{\partial t} = D(t) \left( \frac{\partial^2 MR}{\partial r^2} + \frac{2 \partial MR}{r \partial r} \right) \] (10)

Combining the initial condition (7) and the boundary condition (8), solving Equation 10 gives the following relationship between the dimensionless moisture content and the time change, as shown in Equation 11.

\[ MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -\frac{n\pi^2}{R^2} \int_0^t D(t)dt \right) \int_0^t D(t)dt = D_0 \int_0^t f(t)dt \] (11)

According to related research\(^{[11]}\), the most appropriate empirical relationship is shown in Equation 13.

\[ f(t) = (1 + Fo)^b \] (13)

\[ Fo = \frac{D_0 t}{R^2} \] (14)

Equation 15 is obtained by combining the above equations

\[ MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -\frac{n^2 \pi^2}{1 + b} \left[ (1 + Fo)^{(1+b)} - 1 \right] \right) \] (15)

According to the simplified solution of the spherical coordinate diffusion equation, the simplified variable diffusion model is obtained as shown in Equation 16.

\[ MR = \frac{6}{\pi^2} \exp \left( -\frac{\pi^2}{1 + b} \left[ (1 + Fo)^{(1+b)} - 1 \right] \right) \] (16)

Because all the factors that affect diffusion are attributed to the effective diffusion coefficient, it is inevitable to deviate from the actual situation, so the correction coefficient \( k \) is added in Equation 16, Equation 16 can be transformed to Equation 17.
\[ MR = k \frac{6}{\pi^2} \exp\left( -\frac{\pi^2}{1 + b} \left( (1 + Fo)^{(1+b)} - 1 \right) \right) \]  

(17)

4.2 Model Solving

The experimental data of the typical experimental conditions in 2.1 and 2.2 are brought into Equation 17, and the parameters values in Equation 17 are obtained by regression fitting with Origin9.1 Software, as shown in Table 1.

| Parameters | b   | k   | c₁  | c₂  | R²   |
|------------|-----|-----|-----|-----|------|
| Values     | 10.53 | 1.69 | 1.34 | 600 | 0.99 |

Table 1. Regression Parameter Table

When the parameters are introduced into Equation 17, the variation of moisture content of sludge particles with time under different conditions can be obtained as shown in Equation 18.

\[ X = 1.03X_0 \exp\left( -0.86 \left[ 1 + \frac{1.34 \exp \left( -\frac{600}{R^2 T^2} t \right)}{R^2 T^2} - 1 \right] \right) \]  

(18)

4.3 Model Verification

Figure 4. Comparison of Drying Fitting Curves of Φ 6 mm and Φ 10 mm Sludge balls at 120°C with Experimental Values

Comparison of Drying Fitting Curves of Φ 6 mm and Φ 10 mm Sludge balls at 120°C with Experimental Values are shown Figure 4. It can be seen from Figure 4 that the trend of sludge drying process predicted by the simplified variable diffusion coefficient model are in good agreement with experimental datas.
5. Discussion and Conclusion

(1) As the drying temperature increase, the complete drying time of sludge particles decrease. When the temperature increases from 80°C to 120°C, the complete drying time of sludge particles are significantly shortened, but when the temperature increases from 120°C to 160°C, the complete drying time of sludge particles are not shortened significantly. It is obvious that that increasing the drying temperature can increase the drying rate of sludge, when the drying temperature is increased above the boiling point of water, the drying rate is significantly increased, but the drying rate is not significantly increased after continued increasing temperature.

(2) At the same temperature, as the particle size increase, the complete drying time of sludge particles increase at the same temperature, there is not much difference between the complete drying time for Φ10mm and Φ6mm particles, and the complete drying time significantly increases for Φ18mm particles, It is obvious that the smaller the sludge particle size means the faster the drying rate, and the larger the particle size means the greater the resistance to heat and mass transfer. That is to say that the sludge drying process is controlled by internal migration, and the drying rate is determined by water diffusion rate.

(3) The simplified variable diffusion model of sludge drying is obtained by fitting experimental data, and it can predict the law of the change of the sludge moisture content with time at different drying temperatures and particle sizes.

\[ X = 1.03X_0 \exp \left\{ -0.86 \left[ \left( 1 + \frac{1.34 \exp \left( \frac{-600}{T} \right)}{R^2} \right)^{11.53} t - 1 \right] \right\} \]

The simulation results obtained by the simplified diffusion model are in good agreement with the experimental results, which can well reflect the drying process of sludge particles and provide technical basis for scientifically formulating the drying cycle of sludge particles, adjusting the drying process, improving efficiency, reducing energy consumption, and developing and operating drying equipment.

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