Spreading process simulation and optimization of the flight of municipal sludge rotary dryer

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Abstract. In view of flights spreading process of municipal sludge rotary dryer, the holding capacity and spreading model of flights during sludge drum dryer rotation were established, the influence of setting angle and type of flights on flights tilting angle and material spreading uniformity were investigated through MATLAB programming simulation, and then the structure of flights were optimized. It can be found that the order from large to small of tilting angle of different flight types is arc type, bending type and one-section type, the spreading sludge granules uniformity of bending type flight is better than those of one-section and arc type flight, the hinge connecting part of improved flight can ensure the sludge grabbed, and solve outlet difficult problem of sludge granules at the inlet.

1. Introduction
Nowadays, China’s production has exceeded 40 million tons, and the only twenty percent of sludge had been safely disposed. Municipal sludge contains high moisture content, a large number of pathogenic bacteria, parasitic eggs, toxic and harmful substances such as chromium and mercury. If municipal sludge is not properly disposed, serious secondary pollution problems will inevitably cause and the results of water pollution reduction will be greatly reduced. Municipal sludge has eighty percent of moisture, which causes sludge to be landfilled, composted and incinerated difficultly. It is obvious that efficient dehydration and drying is the key treatment and disposal of sludge. At present, the mature sludge drying processes at home and abroad include rotary drying, multi-layer step drying, rotating disc drying, and fluidized bed drying, etc. Among them, Rotary drying has the advantages of larger processing capacity and lower power consumption but a disadvantage of large heat consumption [1]. If the structure of rotary dryer optimized and the convective heat transfer improved, the rotary dryer will have a wide application prospect in sludge treatment and disposal.

The drying process of granules in rotary dryer is that the granules are scattered, contact with the hot air, and are dried by absorbing heat and evaporating. The flights are used to enhance heat exchange between granules and hot air. Therefore, the thermal efficiency of rotary drum dryer can be improved by correctly selecting the form and structure of flights [2]. Computer simulation is often used to transform and optimize flights structure because computer simulation is more convenient and intuitive than experimental research [3].

In this paper, the holding capacity and spreading model of flights during sludge drum dryer rotation were established, the influence of setting angle and type of flights on tilting angle and spreading...
uniformity of sludge granules were investigated through MATLAB programming simulation, and then the structure of flights was optimized, which provide reference for flights' design in municipal sludge drum dryer.2. The establishment of holding amount of flights and model for the scattering granules.

Aiming at the holding amount of flights and the model for scattering granules, domestic and foreign experts have done a lot of research work, and also proposed many algorithms [4-6]. The main difference between various algorithms is the calculation of granule cross-sectional area on flights. The holding amount can be expressed by the product of granule cross-sectional area, flight length and granule density, and the spreading process can be regarded as the reduction of the granule cross-sectional area of the material during the turning [7,8]. As shown in figure 1, the granule cross-sectional area on the flight is a function of position and geometrical dimensions of flight, drum load, and dynamic angle of repose of granules.

![Figure 1. Drum section coordinate map.](image)

Assuming that granules is a free-flowing particle, angle between granules free surface on flight and horizontal line is always dynamic angle of repose. The calculation formula (1) of dynamic repose angle deduced by Glikin and Schofield is as follows.

$$\tan \phi = \frac{\mu + R_3 \frac{\omega^2}{g} [\cos(\theta + \alpha_3) - \mu \sin(\theta + \alpha_3)]}{1 - R_3 \frac{\omega^2}{g} [\cos(\theta + \alpha_3) - \mu \sin(\theta + \alpha_3)]}$$

(1)

Where $\phi$ — the dynamic angle of repose of granules, rad; $\mu$ — dynamic friction coefficient; $R_3$ — the distance between the flightend and the circlecenter, m; $g$ — gravity acceleration, m/s$^2$; $\omega$ — rotational angular velocity of drum, rad/s; $\theta$—flight corner, rad; $\alpha_3=0^\circ$, horizontal angle at the end of flight , rad.

The geometry of flight is set in the design, and the cross-sectional profile of flight can be represented by a segmented straight line and curve equation. For example, the right angle flight rotates according to coordinates in figure 1. The coordinates of 1, 2, 3 and 4 can be expressed by the function of $R$, $\theta$ and $\alpha_3$. With drum rotating, the holding amount can be expressed by the following formula:

$$M_f(\theta) = \rho_b L \left[ \sum_{i=1}^{4} (x_{i+1}y_i - x_iy_{i+1}) + \frac{\phi(\theta)}{2} - \sin \left( \frac{\phi(\theta)}{2} \right) \cos \left( \frac{\phi(\theta)}{2} \right) \right]$$

(2)

where $\rho_b$ — the bulk density of granules, kg/m$^3$; $L$ — the length of flight, m; $R$ — the radius of drum, m; $R_2$— the distance between the center of drum and point 2, m; $\alpha_2= \theta = 0^\circ$, the horizontal angle of point 2, rad.
2. Determination of parameters in the model

2.1. Angle of repose
The dynamic angle of repose is an important parameter in flight model, but it is difficult to be measured. When the particle motion speed is not high, the angle of repose can be in place of dynamic angle of repose. The angle of repose can be measured by two methods of injection and discharge. In this paper, the angle of repose of sludge granules is 70° by the injection method when the angle of repose of sludge particles with a diameter of 10 mm and the water content of 75%.

2.2. Flight type and size

| Number | Flight type  | Feature size [m] | Schematic diagram |
|--------|--------------|------------------|-------------------|
| 1      | One-section  | L1=0.1           |                   |
| 2      | Bending type | L1=0.1, L2=0.025 |                   |
| 3      |              | L1=0.1, L2=0.05  |                   |
| 4      |              | L1=0.1, L2=0.075 |                   |
| 5      |              | L1=0.1, L2=0.1   |                   |
| 6      |              | L1=0.1, L2=0.125 |                   |
| 7      | Arc type     | L1=0.05, r=0.05  |                   |

where α is mounting angle.

In order to simplify the calculation process, the radius of drum is selected to be 1 m, the type and size of the flight involved in the model are shown in Table 1.

3. Results and analysis

3.1. The effect of setting angle on tilting angle of flight
The tilting angle refers to flight rotation angle at which sludge on flight completely dumped. The larger tilting angle of flight means more uniform spread of sludge granules on the entire upper half of the surface. In this paper, the one-section flight is selected to be brought into the model for research, and the simulation results are shown in figure 2.

As can be seen from figure 2, the tilting angle of one-section type flight increases with the installation angle increasing, but the tilting angle is only 100° when the installation angle increases to 120°, and sludge granules cannot be evenly spread over the entire upper half of circumferential surface.
3.2. The effect of flight type on tilting angle

As can be seen from figure 3, the order from large to small of tilting angle of different flight types is arc type, bending type and one-section type. Under the condition of mounting angle of flights not changed, the structure of flight end can be changed to change tilting angle size of flight. When the flight rotation angle is zero, compared angle between flight end and drum wall surface, it can be found that the larger flight rotation angle means the larger tilt angle. When the flight designed, the angle between flight end and wall surface drum should be ensured large than 180° as far as possible while uniform sludge granules spreading ensured.

3.3. Influence of different types of flights on spreading Uniformity.

In order to make the granules fully contact with the hot air, according to the rationality of spreading, the amount of spreading should be proportional to the spreading location height [7-9]. The granules
are spread on the upper half of the rotary dryer, and the maximum spreading height is at 90°, and the minimum is at 0° and 180°. The comparison of uniformity of different types and sizes of flights are shown in figures 4 and 5.

**Figure 4.** Uniformity comparison of different flights types.

It can be seen from figure 4 that the spreading sludge granules uniformity of one-section flight is the worst, and that of arc type is also unreasonable. In contrast, the spreading pattern of bending type flight is better, the amount of sludge granules spreader at both ends is less, while those at the middle section is more, and those at the initial stage is also large. Therefore, the spreading rule of bending flights with different sizes was further investigated, as shown in figure 5. With the increase of the final section size, the initial spreading amount of flight is gradually reduced, while the final spreading amount of flight is gradually increased. The peak of the middle spreading amount is shifted backward, and the purpose of reasonable spreading cannot be achieved by only changing the end section size of flight.

**Figure 5.** Uniformity comparison of different bending flights sizes.

4. **Structural optimization of flight**

Through model research, it can be found that the amount of flight spreading is closely related to the free surface length of sludge holding section on flight. When the free surface length of granules is proportional to sludge falling distance at the position, the amount of flight spreading is better, and the free surface length of granules can be controlled by designing flight structure.

Assuming that the flight rotation angle is θ, the granules free surface length is \( l(\theta) \), the spreading height is \( h(\theta) \), the coordinate of flight end is \((r_c, 0)\), and the drum radius is \( R \), then the coordinates of E point at flight end can be obtained during rotation process.

\[
h(\theta) = r_c \sin \theta + \sqrt{1 - (r_c \cos \theta)^2} \tag{3}
\]

Assume that the free surface length of granules is proportional to spreading height, and the proportion coefficient is \( k \).

\[
h(\theta) = k \cdot l(\theta) \tag{4}
\]

The intersection line of sludge free surface in cross-section is surrounded by flight contour and drum wall surface, and the intersection length be proportional to spreading height by changing flight contour. The flight contour curve can be obtained by selecting appropriate scale factor. It is assumed that the flight is motionless, the granules free surface is relatively rotated, the angle of repose of sludge is \( \phi \), and the profile coordinate of the papermaking plate is \((x_c, y_c)\), then \((x_c, y_c)\) can be obtained by equations (5) and (6).
Through simultaneous equations (4)-(6), the flight contour curve can be obtained by selecting appropriate value of k, the drum radius is 1m, the angle of repose of sludge granules is 70°, and the coordinates of flight end are (0.2, 0). Bring them into the model, it can be obtained that the contour of flight intersects with drum inner wall when k is equal to 8.7. The contour curve of flight is shown in figure 6.

The resulting flight contour is very similar to the three-arc flight mentioned by Wang Wenzhou [5]. The new flight is spread evenly, and the new flight has uniform sludge granules spreading. However, when flight is located at the drum of rotary drum dryer, the inlet is too narrow to facilitate sludge entering and leaving, so the flight needs to be improved at the inlet. The contact point between flight and cylinder wall is improved, the lower part of flight is fixedly connected with wall surface, and the upper part of flight is hinged with inner wall as shown in figure 7. When the flight moves towards rotary drum dryer bottom, the hinge connecting part will open downwards under the action of gravity, thus the sludge grabbed is ensured, and inlet and outlet difficult problem of sludge granules at the inlet is solved.

\[ \frac{y_e - y_c}{x_e - x_c} = \tan(\phi - \theta) \]  

\[ (y_e - y_c)^2 + (x_e - x_c)^2 = l^2(\theta) \]

5. Summary

- The holding amount of flight and spreading model for sludge granules were established during rotary dryer rotation, and the amount of sludge granules holding capacity was indicated by the change of flight cross-sectional area. The tilting angle refered to flight rotation angle at which sludge on flight completely dumped.
- The order from large to small of tilting angle of different flight types is arc type, bending type and one-section type. Under the condition of mounting angle of flights not changed, the larger flight rotation angle means the larger tilt angle. When the flight designed, the angle between flight end and wall surface drum should be ensured large than 180° as far as possible while uniform sludge granules spreading ensured.
- The spreading sludge granules uniformity of bending type flight is better than those of one-section and arc type flight. When the free surface length of granules is proportional to the spreading distance at the position, the spreading amount is the best, and the free surface length of granules can be controlled by designing flight structure.
- When the flight moves towards rotary drum dryer bottom, the hinge connecting part of
improved flight will open downwards under the action of gravity, thus the sludge grabbed is ensured, and inlet and outlet difficult problem of sludge granules at the inlet is solved.

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