Theoretical calculation of heat transfer coefficient when sludge drying in a nara-type paddle dryer using different heat carriers

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Abstract

Heat transfer characteristics of three typical heat carriers, i.e. saturated steam, thermal oil and flue gas, for indirect paddle dryer were studied. The convective heat transfer coefficient (HTC) of the three heat carriers were theoretically calculated. The contact resistance and penetration resistance were also determined by the penetration model. In the examined range, the significance of different heat resistances were investigated. The convective resistance was dominant in the flue gas based drying systems, while the penetration resistance was dominant in the saturated steam based drying system. In the thermal oil based drying system, both the convective resistance and the penetration resistance were significant. The drying rate of sewage sludge in the different heat carrier based drying systems was simulated by the penetration model. The effect of heat transfer resistances on the drying kinetics of sewage sludge was investigated.

1. Introduction

Industrial and domestic wastewater produce large quantities of residual sludge. Nowadays, a wide reduction of sludge volumes is necessary. Sludge drying is a very effective volume reduction method, and also an important intermediate treatment process as compared with other sludge building materials, etc. Thermal drying of sewage sludge is widely recognized as an efficient means to transform wet sludge into a solid form that allows easy handling, storage, and recycling [1, 2]. There are three categories of dryers for thermal drying of sludge, i.e. indirect dryers [3], direct dryers, and combined dryers [4, 5]. The

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indirect dryers have the advantages of producing minimal amounts of vapors, no pollution of heat carrier and lower energy consumption than direct ones. Reports on drying kinetics of sludge in indirect dryers can be found abundantly [6-11]. Saturated steam and thermal oil are typical heat carriers for indirect dryers. Flue gas is only occasionally used in indirect dryers [8]. Saturated steam, thermal oil and flue gas are markedly different in physical properties and heat transfer (HT) characteristics.

In this study, the HT characteristics of saturated steam, thermal oil and flue gas in a Nara-type paddle dryer were investigated based on theoretical simulation. Drying kinetics of a municipal sewage sludge in the paddle dryer with different heat carriers were also presented.

2. Heat transfer in Nara-type dryer

Fig. 1 shows the 3D structure and sectional view of the Nara-type paddle dryer. The paddle dryer is constructed by wedge-shaped paddles, two hollow shafts, and a jacket. Heat carrier can pass through the paddles, the shaft and the jacket. During sludge drying, sludge is supplied to one end of the dryer and is continuously transferred to the other end. Sludge in the paddle dryer is continuously agitated by the rotating paddles, and is thermally dried by the heat from the heat carrier.

![Fig. 1. Nara-type paddle dryer.](image)

In the indirect dryers, the overall heat transfer resistances are composed of the contact resistance between material and hot wall, the conductive resistance of the hot wall, and the convective resistance between hot wall and heat carrier. It is reasonable to infer that the significance of the three resistances are markedly different for different heat-carriers-based indirect dryers. Fig. 2 shows the HT resistances in the paddle dryer, including the convective resistance between heat carrier and dryer wall, the conductive resistance of dryer wall, and the contact resistance between the hot surface of the dryer and sludge bulk. Different heat carriers are mainly characterized by their different convective resistances, whose effect on sludge drying kinetics will be discussed subsequently based on the contact drying model (penetration model). The penetration resistance is the heat transfer resistance in sludge bulk.

![Fig. 2. HT resistances in paddle dryer.](image)

In this study, three kinds of heat carriers were studied, i.e. saturated steam, thermal oil and flue gas. Since these three heat carriers are much different in physical properties, the inner structure of the dryer
paddles were differently constructed for different heat carriers. Fig. 3 shows the inner structure of paddles for saturated steam, thermal oil and flue gas, respectively. Detailed description of the inner structure of paddles can be found elsewhere [3, 12].

![Fig. 3. Inner structure of paddles for different heat carriers.](image)

It should be noted that the outline dimensions of the paddle dryer, for different heat-carrier-based drying study, are identical. A typical municipal sewage sludge from China was adopted for theoretical study. The detailed description of the sewage sludge can be found in our previous study [11].

3. Determination of heat transfer coefficient (HTC)

3.1. Determination of convective resistance of heat carrier

When saturated steam was used as heat carrier, as shown in Fig. 3(a), the saturated steam flowing in the hollow shafts can be considered as a pipe flow. Therefore, the condensation-HTC of saturated steam was calculated based on the following equation [13, 14]:

\[
h_{ss} = 0.555 \left[ \frac{g \rho_w (\rho_w - \rho_s) \beta_w^3 [r + 0.68c_{ps}(T_s - T_w)]}{\mu_w d (T_s - T_w)} \right]^{1/4}
\]  

(1)

When thermal oil was used as heat carrier, as shown in Fig. 3(b), the heat transfer coefficient of thermal oil forced flowing in pipe can be calculated by Dittus-Boelter correlation [15]:

\[
Nu_{oil} = 0.023 \left[ \frac{w_{oil}^{0.8} \left( \frac{\rho P}{\mu} \right)^{0.3} \alpha_{oil}^{0.7}}{d_{oil}^{0.2}} \right] \]  

(2)

\[
h_{WO} = 0.023 \left[ \frac{w_{oil}^{0.8} \left( \frac{\rho P}{\mu} \right)^{0.3} \alpha_{oil}^{0.7}}{d_{oil}^{0.2}} \right]
\]  

(3)

It should be noted that eqn.(2) is only valid when \(Re\) is in the range of \(10^4 – 1.2 \times 10^5\), and \(Pr\) in the range of \(0.7 – 120\). Therefore, the velocity of thermal oil was chosen in the range of \(0.2 – 1.8\) m/s for calculation.

When flue gas was used as heat carrier, as shown in Fig. 3(b), The convective HTC of flue gas \(h_{WG}\) can also be simulated by Dittus-Boelter correlation [15]. The HTC \(h_{WG}\) of flue gas forced flowing in pipe was determined by the equation:

\[
h_{WG} = 0.023 \left( \frac{w}{V} \right)^{0.8} \frac{\left( \rho P \right)^{0.3}}{d} \]  

(4)

Since eqn.(4) is only valid when \(Re\) is in the range of \(10^4 – 1.2 \times 10^5\), the velocity of flue gas was chosen in the range of \(6.0 – 16.0\) m/s for calculation.
3.2. Determination of conductive resistance of dryer-wall

The stainless steel of 304# (0Cr18Ni9Ti) is commonly used as dryer material. It is supposed that the thickness of dryer wall was $\delta = 5$ mm. Therefore, the HTC of the dryer wall can be determined by equation:

$$h_{\text{cond}} = \frac{\lambda_S}{\delta} \quad (5)$$

3.3. Determination of contact resistance between sludge and wall

The contact resistance $h_{\text{cont}}$ is given by the following equation [16]:

$$h_{\text{cont}} = k + (1 - k) \left[ \frac{1}{2} + \frac{2 \lambda_s / d}{\sqrt{2} + (2l + 2 \omega) / d} + 4C_i \right] \quad (6)$$

where $\alpha_{wp}$ is the heat transfer coefficient for a single particle and is calculated by:

$$\alpha_{wp} = \frac{4 \lambda_s}{d} \left[ \ln \left( \frac{1 + \frac{2l + 2 \delta}{d}}{1 + \frac{d}{2l + 2 \delta}} \right) \right] \quad (7)$$

Detailed description of contact resistance determination method can be found in our previous study[11].

3.4. Heat penetration coefficient (HPC) in sludge bulk

The HPC in sludge bulk is given by [17]:

$$h_{\text{penetration}} = \frac{2}{\text{erf}(\xi)} \sqrt{\frac{(\rho C_p)_{\text{bed}}}{\pi \tau}} \quad (8)$$

Detailed description of contact resistance determination method can also be found in our previous study [11]. Fig. 4 shows the HPC of a sewage sludge bulk at different moisture content. The physical properties of the sludge were shown in Table 1 [11].

Table 1. Thermal conductivity, thermal diffusivity, packing density and specific heat capacity of dried sewage sludge bed at 25°C.

<table>
<thead>
<tr>
<th>Thermal conductivity (W/m °C)</th>
<th>Thermal diffusivity (10⁻⁷ m²/s)</th>
<th>Packing density (kg/m³)</th>
<th>Specific heat capacity (J/kg °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.134</td>
<td>1.60</td>
<td>758.20</td>
<td>1040+2.727°C</td>
</tr>
</tbody>
</table>

Fig. 4. HPC in sludge bulk.
4. Results and discussion

Fig. 5 shows the percentage of different thermal resistances at different heat carrier based drying systems. In the saturated steam based drying system, the penetration resistance is the main thermal resistance which accounted for 66.1% of the total thermal resistance, while the convective resistance only accounted for 7.8% due to the high HTC of saturated steam. In the thermal oil based drying system, the convective resistance and the penetration resistance are the main thermal resistances. The velocity of thermal oil had an obvious effect on distribution of thermal resistances. In the flue gas based drying system, the convective resistance accounted for more than 90% of the total thermal resistance when the current velocity of the flue gas was lower than 12 m/s. Fig. 6 shows the overall HTC of the drying system, $h_{total}$. In the examined range, saturated steam was the most efficient heat carrier for indirect drying system. The overall HTC Flue gas was so much lower than saturated steam and thermal oil that it was not an appropriate heat carrier for indirect drying. Although the low convective HTC of flue gas can partly be overcame by enhancing gas temperature, this was strictly limited by the dryer material.

Fig. 5. Percentage of different thermal resistances (Steam: 200 °C; Oil1: 200 °C, 1.5 m/s; Oil2: 200 °C, 0.6 m/s; Gas1: 200 °C, 6 m/s; Gas1: 200 °C, 12 m/s; Average particle diameter: $d = 1.0 \times 10^{-4}$ m).

Fig. 6. Overall HTCs based on different heat carriers (Steam: 200 °C; Oil1: 200 °C, 1.5 m/s; Oil2: 200 °C, 0.6 m/s; Gas1: 200 °C, 6 m/s; Gas1: 200 °C, 12 m/s).
The drying rate of the above referred sewage sludge in the different heat carrier based drying systems can be simulated by the penetration model [16]:

\[ \dot{m} = \frac{\Delta H \exp(-\varepsilon^2)}{\left(1/h_{\text{total}} + 1/h_{\text{penetration}}\right)\Delta H_{\text{total}}} \]  

(9)

Fig. 7 shows the simulated drying rates of the sewage sludge in the different heat carrier based drying system. It can be found that, under the same heat carrier temperature, the higher overall HTC led to the higher sludge drying rate. The drying rate of saturated steam or thermal oil based drying system was much higher than that of flue gas based drying system.

During calculation, it was supposed that the temperature of heat carrier was a constant. However, since thermal oil and flue gas were sensible heat flow, their temperature will decrease continuously during drying. This will make the actual drying rate curve more steeper. As discussed above, the contact resistance \( h_{\text{cont}} \) was strongly depended on particle diameter. The particle diameter of \( 1.0 \times 10^{-4} \) m was used for \( h_{\text{cont}} \) calculation in this study. In fact, the particle diameter of sludge was not a constant during drying process, since sludge drying is accompanied by phase changing (i.e., pasty, lumpy and granular phases with decrease of moisture content) and granule formation. The particle diameters in the pasty, lumpy and granular phases should be distinctively considered for theoretical calculation.

Fig. 7. Sludge drying rate in different heat carrier based drying system (◊: Saturated steam at 200 °C; □: Thermal oil at 200 °C, 1.5 m/s; ●: Thermal oil at 200 °C, 0.6 m/s; ∆: Flue gas at 200 °C, 6 m/s; ○: Flue gas at 200 °C, 12 m/s; *: Flue gas at 400 °C, 12 m/s).

5. Conclusions

Based on the above discussion on indirect paddle type dryer, it can be concluded that saturated steam is a much more ideal heat carrier than thermal oil and flue gas, due to its high thermal capacity and high HTC. Under the same evaporation load, the saturated steam based drying system can be operated under lower drying temperature than thermal oil or flue gas based drying system. Nonetheless, it should be noted that saturated steam has a higher demand for metal material of paddle dryer due to its higher operating pressure.
Acknowledgements

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References