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Research Paper

Assessment on thermal behavior of municipal sewage sludge thin-layer during hot air forced convective drying

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HIGHLIGHTS

- Thermal behavior of sewage sludge thin layer in hot air drying was revealed.
- Effects of hot air temperature and speed on temperature of thin layer were gained.
- Average surface heat and mass transfer coefficients were determined.
- Dimensionless heat transfer correlation in 1st falling rate stage was developed.

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ABSTRACT

Thermal behavior on the municipal sewage sludge thin-layer in a bench-scale hot air forced convective dryer was investigated at a hot air temperature range of 100–160 °C and three hot air speeds (0.6, 1.4, and 2.0 m s^{-1}). The drying process presented four distinctive stages: a warm up stage, a constant rate stage, the first and the second falling rate stages. The temperature of the thin-layer increased rapidly in the first falling rate stage, whereas it rose slightly in the second falling rate stage. The average surface heat transfer coefficients in the first falling rate stage were about 3 times more than that in the second falling rate stage. The average surface heat and mass transfer coefficients at 0.6 m s^{-1} hot air speed increased by about 39% and 91% with an increase of the hot air temperature from 100 to 160 °C. The dimensionless surface heat transfer correlation of the sewage sludge thin-layer was obtained for the first falling rate stage. The model could fit the experimental data within ±25% deviation.

1. Introduction

With the increasing population, industrialization, and effluent quality standards, sewage sludge is largely generated from municipal waste water treatment worldwide [1–3]. High water content has been a critical problem for sewage sludge treatment and disposal further [4]. Thermal drying is an indispensable step to further reduce moisture content of sewage sludge from waste treatment for improving efficiency of transporting and processing [5–7]. The thermal drying technique can be applied prior to further thermal processing of the sewage sludge, such as conventional incineration, co-incineration with coal or other fuels, or pyrolysis [8], especially in some developed countries where dried sludge is frequently used in coal-fired power stations and cement kilns [9]. The moisture content of the sewage sludge required is no more than 35% (dry base) for conventional incineration system [8]. The thermal drying behavior of the sewage sludge is a complicated process which is related to drying methods and operating conditions [7]. The hot air convective drying technique of sewage sludge is a convenient method for the power plant system, which can be widely used to utilize low-quality energy such as flue gas waste heat. The heat is transferred to the sludge in a convective dryer through a hot gaseous medium (usually air or flue gas) which contacts directly with the sludge surface [3]. The convective drying of the sewage sludge is a complicated process involving simultaneous heat and mass transfer which is influenced by many factors such as operation conditions, the degree of hydration and pore structure and physicochemical properties of the sewage sludge. Developing a dimensionless heat and mass transfer correlation for convective drying process of the sewage sludge is important for better understanding its thermal drying behavior and even to provide basic data for dryer design and further numerical simulation of thermal drying characteristics of the sewage sludge.

At present, a variety of experimental investigations primarily focused on the heat and mass transfer characteristics of the agricultural products during low temperature drying. The products' temperatures increased sharply at the initial stage for carrot slices drying [10], potato and apple slices drying [11], then grew slightly

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as the drying processed and stabilized at the final period of drying. The surface heat transfer coefficients of grain thin layer during hot air drying were estimated based on an inverse method combined with measured values of instantaneous surface temperature and average moisture content of the sample by Miketinac et al. [12] Velić et al. [13] investigated the influence of the hot air speed (0.64–2.75 m s^{-1}) on the surface heat transfer coefficients of apple slice at hot air temperature of 60 °C. Tremblay et al. [14] also found that the surface heat transfer coefficients of the red pine slices at 56 °C increased greatly with the hot air speed rising from 1.0 m s^{-1} up to 5.0 m s^{-1}. Villa-Corrales et al. [15] highlighted the influence of the hot air temperatures (50–70 °C) on the surface heat transfer coefficients of mango slice at hot air speed of 0.2 m s^{-1}. Barati and Esfahani [16] established a mathematical model predicting the temperature variation in mango slice under a convective drying boundary condition. The surface heat transfer coefficient of celery root in a natural convection drying was evaluated by an inverse problem formulation [17]. A numerical model for heat and mass transfer of granular products in a fixed-bed tunnel dryer was developed based on a thin layer model and drying kinetics [18]. Jaturonglumlert and Kiatsiriroat [19] derived the heat and mass transfer characteristics of fruit leather according to a dimensionless heat transfer correlation proposed by Lebedev [20]. Following the same correlations, Ol'shanskii [21] also determined the heat transfer coefficients of moist materials (porous ceramics, sole leather, asbestos sheets, clay and woolen felt). Font et al. [1] revealed the skin effect in the heat and mass transfer model for small sewage sludge spheres and cylindrical tablets drying. In addition, thin-layer drying is a convenient approach for investigating diffusion and convection transient problems, which may be used whenever diffusion inside the material is much faster than the diffusion across the boundary of the solid [22]. A slice of investigation mainly described thin layer drying kinetics of other samples [23,24], but as of now, no information is available on the potential impact of the drying behavior for municipal sewage sludge thin layer. Especially the heat and mass transfer characteristics of the sewage sludge thin layer are not found in the literature.

In the present work, heat and mass transfer behaviors of the sewage sludge thin-layer during hot air forced convective drying are highlighted. The effects of hot air temperatures and speeds on the average temperature, surface temperature and surface heat and mass transfer coefficients of the sewage sludge thin layer are estimated. The dimensionless heat transfer correlation of the thin layer in the first falling rate period is also obtained.

2. Materials and methods

2.1. Materials

The sewage sludge sample was collected from a municipal wastewater treatment plant in Beijing, China, which was after mechanical dewatering and natural curing. The pH value of the sludge sample was 6.71; the contents of total nitrogen, total phosphorus, total potassium and organic matter of the sludge were 56.6, 49.1, 9.3 and 667.6 g kg^{-1}, respectively [25]. The sample was placed in a closed container for 24 h after being fully stirred, in order to get more homogenization sample. Sewage sludge samples were stored at 6 °C in a refrigerator before the drying experiment.

2.2. Experimental apparatus and procedure

The experiments were carried out in a bench-scale convective dryer shown in Fig. 1. The air induced from a frequency conversion fan was heated by a 3000 W heater. Then, the hot air was dehumidified through the dehumidification unit containing calcium oxide drying agent and circulated about 15 minutes. About 52 g of the prepared sewage sludge sample was uniformly spread as a thin layer on a square steel tray (80 mm × 80 mm × 10 mm). Outer surface including the bottom and other sides of the steel tray covered by a layer of foamed ceramics was insulated approximately. The samples had initial moisture content of 0.93–0.98 kg kg^{-1} (d.b.). The thickness of the thin layer was about 10 mm. The sewage sludge thin layer on the tray over a digital balance was placed in the drying chamber and dried by the convective heat exchange of the hot air. Drying experiment was finished when the mass change rate was less than 0.002% in 10 minutes. The more detailed description about the experimental apparatus was presented in previous work [26]. Three temperature sensors (PT100) were used to measure the air temperature, the surface temperature and bottom temperature of the thin layer. During the drying process, mass of the thin layer was recorded at an interval of 90 s by the digital balance (OHAUS; CP413, China) with an accuracy of 0.001 g. The experimental data on time related changes in temperature and moisture content during drying may be used to determine the heat and mass transfer coefficients.

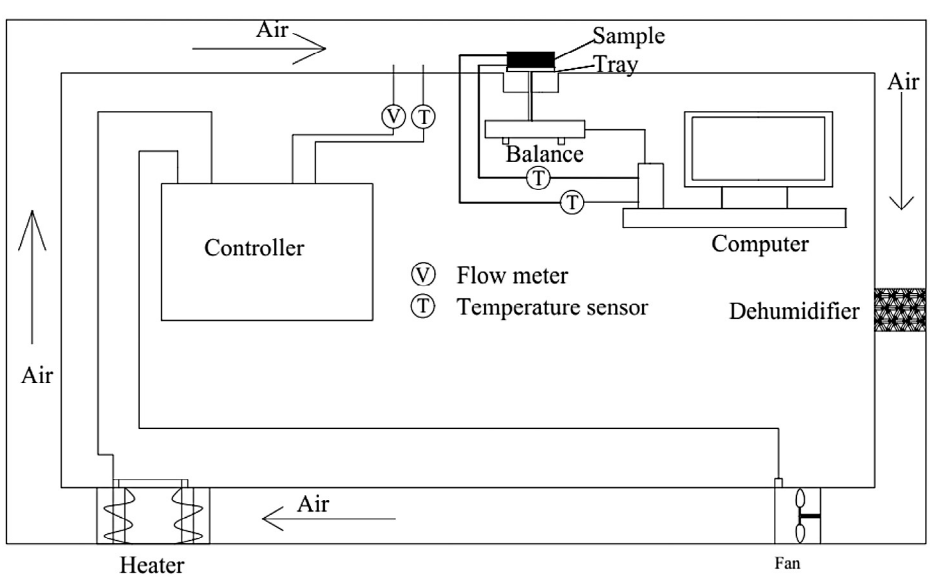

Fig. 1. Convective dryer setup.