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Isothermal hot air drying behavior of municipal sewage sludge briquettes coupled with lignite additive

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HIGHLIGHTS

- Effects of lignite on convective drying of sewage sludge briquette were conducted.
- Influence of hot air temperatures on drying kinetics of sewage sludge were studied.
- Midilli model showed perfect prediction for sewage sludge/lignite thermal drying.
- Lignite could improve the drying behavior of sewage sludge briquette over 120 °C.

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ABSTRACT

Isothermal drying behaviors of the municipal sewage sludge briquettes were investigated based on a laboratory-scale hot air forced convective dryer at 1.5 m s^{-1} air speed. The influences of drying temperatures (60–180 °C) and lignite as a typical additive with 10% dosage on the drying kinetics of the sewage sludge were highlighted. A considerable shrinkage and cracking of the sewage sludge briquettes presented in the drying process, and there were many hollow cavities formed in the final drying stages. The average drying rates of the sewage sludge/lignite blend in the whole falling rate periods were higher than that of the raw sewage sludge. The Midilli models gave good agreement between experimental and predicted moisture ratios of the raw sewage sludge or sewage sludge/lignite blend with the highest R^2. The apparent activation energies of the raw sewage sludge or sewage sludge/lignite blend in the first falling rate periods were higher than that in the second falling rate periods. Adding lignite could obviously improve the drying behavior of the sewage sludge briquettes over 120 °C.

1. Introduction

With the increasing population, industrialization, and effluent quality standards, sewage sludge is largely generated from municipal waste water treatment worldwide [1]. There are more than 20 million tons of sewage sludge being produced annually in China [2]. Around 11.5 millions of tons of dry sewage sludge in the European Union are produced yearly [3]. Sludge handling has been one of the key environmental problems, however, the basic information on sludge production, treatment, and disposal is still insufficient [4]. It can also be utilized as a solid fuel and burned directly for the generation of heat and power. However, the sewage sludge is characterized by its high moisture content, low calorific value, and low bulk density, which result in a low conversion efficiency as well as difficulties in its collection, grinding, storage and transportation. Especially, high moisture content in sewage sludge is a critical factor that determines disposal options, such as direct land application, composting, landfill, or incineration [5]. Mechanical dewatering including filtration and centrifugation can be firstly applied to make the moisture content of the sewage sludge be reduced to about 80% [6]. Dried sludge is preferred when the sludge is either to be incinerated or utilized as a soil amendment. Conventional incineration must be preceded by pre-drying of sewage sludge to about 25% dry base content [7]. The thermal drying has received much attention and become a major sludge processing technology after mechanical dewatering [8]. Generally, three methods are applied for sewage sludge thermal drying; convective drying [1], conductive drying inside a paddle dryer [9] and radiate drying [10]. Convective drying among all thermal

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Nomenclature

D_0	diffusion factor ($m^2\ s^{-1}$)
D_{eff}	effective moisture diffusivity ($m^2\ s^{-1}$)
E_a	apparent activation energy (kJ mol^{-1})
L	thickness (m)
MR	moisture ratio
R	gas constant (kJ mol^{-1} K^{-1})
t	time (s)
T	temperature (°C)

Superscripts and subscripts

0	initial
eff	effective

drying manners is a traditional and proven technique in drying industry, which can also improve stabilization of sewage sludge through inactivation of pathogenic biological organisms [11]. The sludge in convective dryers is heated through a hot gaseous medium such as air or flue gas from an incinerator or power plant [1]. However, sewage sludge to be dried is still highly difficult due to the existence of colloidal materials and extracellular polymeric substances within them, which bind water molecules strongly to solid surfaces or capture them inside the cells or flocs [12]. Adding additives into the sewage sludge is usually more attractive from economic and environmental viewpoints. The physical additives can form a permeable and more rigid lattice structure which can remain porous during drying of sludge. In addition, by combining a moisture absorbing material (a hydro-gel) such as lignite with the sludge, the absorbent acts as a drying aid to control agglomeration. The lignite is a readily available cheap natural hydro-gel [13], and the dried lignite which has a higher calorific value would improve combustion behavior of the overall sludge blend in the incinerator, and reduce the need to more expensive fossil fuels. According to Thapa et al. [14], lignite particles can agglomerate with the flocculated sludge by polymer bridging, which can improve the dewatering properties of the flocculated sludge. Hoadley et al. [15] confirmed that adding of lignite into the anaerobically digested sludge led to a more productive drying process and improved product quality.

Moreover, among the explored sewage sludge upgrading methods, densification (or pelletization) is also an available route for solid fuel production in addition to thermal drying. The wastes are subjected to consolidation, e.g. briquetting, pelletizing or granulation, which is a pressure agglomeration method where loose material is compacted into a dense mass. The processed wastes, in the form of granules or briquettes, can be stored safely with no risk of secondary environmental pollution, and can be efficiently transported, and co-fired with coal in conventional coal-fired power plants [16]. Dust and odors are also minimized since the fuel pellets are homogenized and as such smaller particles are trapped into the material matrix [17]. The compact processes can increase the bulk density of solid fuels up to at least 250 kg m^{-3}, and the bulk density values for granular or briquetted wastes are much higher [16]. Li et al. [18] revealed that the compacted fuel logs made of the major combustibles in municipal solid waste (MSW) could have a heating value equal to or higher than 20 MJ kg^{-1}.

Kinetics analysis on drying is a significant approach for better elucidating the moisture migration mechanisms, and giving available information for designing and improving a dryer [19]. Font et al. [20] revealed the thermal drying kinetics of small sewage sludge spheres (2.5 cm diameter) and cylindrical tablets (1-cm height and 6.6-cm diameter) in 30–65 °C temperature range, and developed a mathematic model with a well time correlation of moisture content. Celma et al. [21] investigated the thin layer drying behavior of sewage sludge at hot air temperatures of 30–50 °C, and derived that the activation energy was 30.15 and 36.70 kJ mol^{-1}, at air speeds of 0.9 and 1.3 m s^{-1}, respectively. The isothermal drying characteristics of three different municipal sewage sludge samples were also investigated in a thermogravimetric analyzer [22]. The average activation energy was 17.30 kJ mol^{-1} within 100–175 °C. Zhang and Chen [23] highlighted that the apparent activation energy of the sewage sludge in the isothermal drying was less than that in the nonisothermal drying based on a TG technique.

Although a host of work has been addressed on drying processes of sewage sludge briquette, less investigation is conducted to characterize the potential impact of the thermal drying behavior for sewage sludge briquette coupled with additives. Especially, the drying kinetics of sewage sludge by adding the lignite additive based on two falling rate stages is not found in literatures. In the present work, the isothermal drying behavior of the municipal sewage sludge blending with a typical additive (lignite) is explored based on a bench-scale hot air forced convective dryer. The effects of temperatures and lignite additive on the drying kinetics of the sewage sludge briquettes in two falling rate stages are highlighted. This research will provide fundamental data for further upgrading the thermal drying characteristics of the municipal sewage sludge briquettes.

2. Methods

2.1. Experimental facility and test samples

The sewage sludge sample was collected from a municipal wastewater treatment plant in Beijing, China, which was after mechanical dewatering. The pH value of the sludge sample is 6.71, the content of total nitrogen is 56.6 g kg^{-1}, the content of total phosphorus is 49.1 g kg^{-1}, the content of total potassium is 9.3 g kg^{-1}, the content of organic matter is 667.6 g kg^{-1} [23]. The samples were placed in a closed container for 24 h after being fully stirred, in order to get homogenization sample. Sewage sludge samples were stored at 6 °C in a refrigerator before the drying experiment to preserve drying properties of the sewage sludge during storage. The pulverized Chinese lignite was obtained from a power plant (Sanhe, China) and sieved by using 325 μm sieves. Sewage sludge and lignite powder were mixed with lignite powder blending ratio of 10% and manually homogenized. The initial moisture content of the raw sewage sludge and the lignite were obtained by placing the samples in an oven (KUNTIAN; 101-00B, China) for about 24 h at 105 °C [24]. The initial moisture content of raw sewage sludge was 4.65–4.82 kg/kg (d.b.), while initial moisture content of the lignite powder was 0.03–0.04 kg/kg (d.b.). Initial moisture content of sewage sludge/lignite blend was 0.74–0.77 kg/kg (d.b.). 20 ± 1 g of sewage sludge or sewage sludge/lignite blend was shaped in a briquette (cake) (10 mm thickness and 40 mm diameter) in a molding machine (HEBI; XL140118, China). The compaction was performed at under room temperature without adding any binder and at pressures up to 0.1 MPa. Proximate analyses of the sewage sludge sample and the lignite sample were performed in a thermogravimetric analyzer (TGA/SDTA851, Mettler Toledo) with a precision of 0.001 mg, the detailed measuring method was given by Mayoral