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Evaluation on the air-borne ultrasound-assisted hot air convection thin-layer drying performance of municipal sewage sludge

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ABSTRACT

The thin-layer drying behavior of the municipal sewage sludge in a laboratory-scale hot air forced convective dryer assisted with air-borne ultrasound was investigated in between 70 and 130 °C hot air temperatures. The drying kinetics in the convective process alone were compared to that for ultrasound-assist process at three ultrasound powers (30, 90, 150 W). The average drying rates within whole drying temperature range at ultrasound powers of 30, 90 and 150 W increased by about 22.6%, 27.8% and 32.2% compared with the convective drying alone (without ultrasound). As the temperature increasing from 70 °C to 130 °C, there were maximum increasing ratios for the effective moisture diffusivities of the sewage sludge in both falling rate periods at ultrasonic power of 30 W in comparison with other two high powers. In between the ultrasound powers of 0 and 30 W, the effect of the power on the drying rate was significant, while its effect was not obvious over 30 W. Therefore, the low ultrasonic power can be just set in the drying process. The values of the apparent activation energy in the first falling rate period were down from 13.52 to 12.78 kJ mol^{-1}, and from 17.21 to 15.10 kJ mol^{-1} for the second falling rate period with increasing the ultrasonic power from 30 to 150 W. The values of the apparent activation energy in two falling rate periods with the ultrasound-assist were less than that for the hot air convective drying alone.

1. Introduction

A large amount of municipal wastewater produced from daily life of human need to be treated, in which the remaining substances has been known as sewage sludge that contains excess bacterial biomass that may lead to serious health and environmental problems [1–3] if without further disposing on it. The minimization of sludge production and recovery of valuable byproducts or bioenergy is becoming increasingly critical for sustainable sludge management [4]. However, the high water content may greatly hinder the recovery of energy and byproducts from sewage sludge [5]. In general, mechanical dewatering for sewage sludge is firstly used to reduce its moisture content to about 80% [6], but the sewage sludge after being mechanical dewatering still requires the deep drying to achieve the reduction of transport and storage cost and the increase of treatment efficiency [5,7]. Thermal drying techniques, especially convective drying technique has been widely applied to the deep drying processing of the sewage sludge [8,9], for the reason that it can utilize directly waste heat from flue gas in power plants system or other industrial processes.

To further improve the drying performance of samples, the ultrasound (US) technique emerging as a promising method has been applied into the conventional drying system [10]. Ultrasound, known as a cyclic sonic wave, can be transferred away from the emitter with the help of water or air, thus the US technique can be used in drying applications [11]. Ultra sonication is a known technique for disrupting sludge floc [12], and then there is a significant drying time reduction for ultrasonic hybrid drying compared with the conventional drying [13]. The ultrasonic energy can activate a series of mechanisms (heat, diffusion, mechanical rupture, chemical effects), which can enhance physical and chemical reaction processes [14,15]. There are two main ways for ultrasonic devices assisting drying processes: the ultrasonic transducers are directly contacted into the samples during drying; the ultrasonic transducers work without direct contact between the vibrating element and the samples [16]. Frequencies used commonly in ultrasonic-assisted convective drying are between 20 kHz and 40 kHz [13]. Chu et al. [17] suggested that the floc structure of the waste-activated sludge can be effectively disintegrated at the

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Nomenclature

CV	convection drying
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})
F	the value of F-test
L	thickness (m)
MR	moisture ratio
P	probability
R	gas constant (kJ $mol^{-1}\ K^{-1}$)
t	time (s)
T	temperature (°C)
US	ultrasound

Subscripts

0	initial
e	equilibrium
eff	effective
t	any moment

frequency of 20 kHz. Although the direct contact technique can promote the drying process because of good ultrasonic energy transfer from the vibrating element to the samples, the technique may be difficulty to adapt to conventional hot air drying process. An indirect contact technique is developed based on the air-borne ultrasound, which can easily be coupled with the conventional hot air drying. Although it may have a relative low efficient ultrasonic energy transfer compared to the direct contact one due to the acoustic impedance mismatch and the energy absorption by the air at ultrasonic frequencies, it can make the air-borne ultrasound be combined conveniently with industrial drying systems [16]. The efficiency of ultrasonic emitters, which use air as a resonance media can reach to 80% in recent developments [13].

Much works concerning the ultrasound hybrid technique of the convective drying mainly focus on the food drying [11,14,18]. Gamboa-Santos et al. [16] explored the effect of the air-borne ultrasound on improving the convective drying of strawberry with three ultrasound powers (0, 30 and 60 W) and in the air temperatures of 40, 50, 60 and 70 °C, and then stated that the power ultrasound significantly improved the effective moisture diffusivity. Bantle and Hanssler [11] investigated the drying behavior of salted codfish in a hybrid drying system with high-intensity air-borne ultrasound applied in convective drying, and revealed that the convective drying assisted by ultrasound at 20 °C is better than the process at 30 °C without ultrasound. Bantle and Hanssler [11], Bantle and Eikevik [13] stated that the ultrasound was emitted perpendicular to the surface of the fish product at a distance of 20 mm. For the ultrasound-assisted convective drying of sewage sludge, only one existing report is that Zhao and Chen [19] by means of numerical modeling, stated that the enhancement effect of the ultrasound on the average drying rate of sludge is more obvious at 65 °C hot air temperature than that at 40 °C under the uniform acoustic energy density. They also found that the ultrasonic irradiation can change the pore size distribution in sludge.

In addition, thin-layer drying is considered to be an effective approach in addressing the complex problems of diffusion and convection transient existing in the drying process [20], which can be helpful for further developing the deep-bed drying model [21–23]. Some researchers have applied the thin layer drying approach to investigate the complex drying behavior of fruits [24–26], agricultural products [27–29], wet fuels [30,31] and sewage sludge [32], etc.

As mentioned above, some works have be conducted on the convective drying assisted by the ultrasound (US) technique for foods or just on the convective thin-layer drying behaviors of various materials, but the investigation concerning thin-layer drying under the US technique assisted convective is rarely. Especially the convective thin-layer drying kinetics for sewage sludge with the US-assist technique is still not found in the literatures. The main purpose in this current work is to evaluate the thin-layer drying behavior of the municipal sewage sludge during hot air forced convective drying assisted by air-borne ultrasound. The effects of hot air temperatures and the ultrasound powers on the thin-layer drying kinetics of the municipal sewage sludge are also addressed.

2. Methods

2.1. Materials

The sewage sludge sample after mechanical dewatering was collected from a municipal wastewater treatment plant in Beijing, China. The samples had initial mass of 36 ± 1 g with initial moisture content of 0.80–0.85 kg/kg (w.b.). The thickness of the thin layer was about 10 mm. 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 [33]. The sample was fully stirred in order to homogenize the samples, and then the homogenized sewage sludge samples were stored at 6 °C in a refrigerator before each experiment.

2.2. Experimental setup

The experiments were carried out in a laboratory-scale hot air forced convective dryer as shown in Fig. 1.

The drying system was consisted of a fan (XINXING; 150FLJ, China), a 3000 W heater, a digital balance (OHAUS; CP413, China) with an accuracy of 0.001 g, a dehumidification unit (calcium oxide), a temperature controller (YUYAO; XMTD-808P, China), a digital anemometer (TECMAN; TM826, China), a temperature sen-

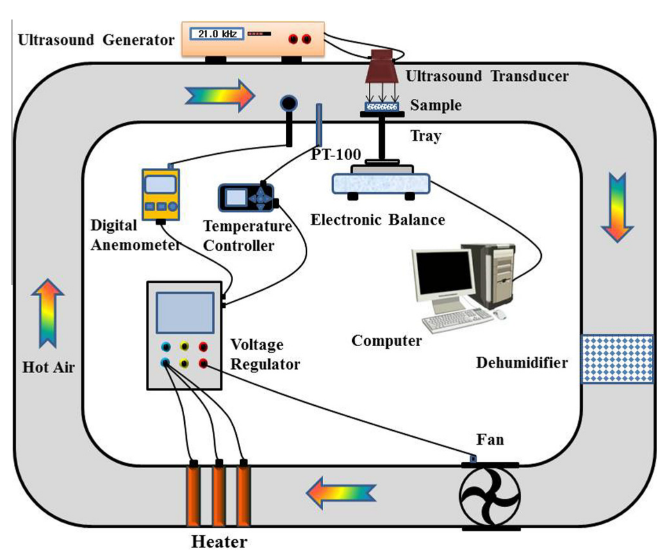

Fig. 1. Ultrasound-assisted convective dryer setup.