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Changes in pore size distribution inside sludge under various ultrasonic conditions

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The pore size distribution is quite significant for determining the transport capacity of heat and moisture in sludge during the drying process. It is crucial to investigate the transformation of the pore size in sludge under sonication. In this paper, the microstructures of pores inside sludge before and after ultrasonic treatment with various ultrasonic conditions were observed using a microscope. Fractal geometry and image analysis were combined to quantitatively identify the evolution of pore size in sludge undergoing various acoustic energy densities and treatment times. The surface fractal dimension (d_f) was applied to characterize the pore size distribution of sludge. The results confirmed that sonication has a positive influence on the characteristics of pore structure inside the sludge and that the average pore size increases with increasing ultrasonic energy level, as determined by both acoustic energy density and treatment time. The d_f appropriately characterizes and quantifies the evolution of the pore size distribution of sludge under various ultrasonic conditions. This work is quite valuable for further investigating and evaluating moisture removal in the sludge drying process assisted by ultrasonic treatment.

1. Introduction

Sludge treatment and disposal are increasingly significant for environmental requirements. High moisture content becomes a major barrier for reducing, recycling and disposing of sludge. Sludge moisture content is a critical parameter governing the feasibility of various final disposal routes, such as direct land application, composting, landfill, and incineration. For this reason, thermal drying of sludge is absolutely necessary after mechanical dehydration. However, the huge energy consumption becomes a serious problem in the application of thermal drying in sludge treatment. The demands of sustainable technologies for sludge treatment are urgent due to economic constraints [1].

In recent decades, various types of sludge pretreatment methods have been presented for improving sludge dewaterability, including biochemical and physical regulation [2–4]. Ultrasound is regarded as one of most efficient techniques applied in the pretreatment of waste activated sludge (WAS) [5–17]. Ultrasonic treatment can break up the sludge flocs and rupture the cell membranes of microorganisms, allowing the intracellular and extracellular contents to be released into the aqueous phase [6–10]. Sonochemical reactions occur as a result of cavitation. Cavitation bubbles alternately grow and collapse, caused by the alternate compression and expansion cycles of sound waves traveling through the liquid. The bubble collapse generates a unique chemical environment: localized temperatures of several thousands of degrees (5000 K) and hundreds of atmospheres in pressure, which also dissociates the water molecules to produce reactive hydroxyl radicals. In addition, the intense shear forces caused by ultrasonic mechanical effect can destroy the extracellular polymeric substances (EPS) and disintegrate floc particles of sludge [11–17].

The ultrasonic effects of thermal drying of sludge differ from those of dewatering of liquid sludge. In recent years, the majority of available experimental studies indicated that ultrasound is useful in enhancing mass transfer during vegetable and fruit drying processes without significantly heating the materials [18–24]. The “sponge effect” is currently recognized as the main mechanism of ultrasound enhancing the migration of moisture in a porous medium. The acoustic propagation in a solid-liquid porous medium produces a rapid series of alternating compressions and rarefactions (sponge effect), which favors the migration of moisture through natural or caustically created channels [20–26]. However, the mechanism of ultrasound enhancing mass transport process is complicated and undefined; the “sponge effect” is just one of the aspects of the complicated mechanism. Therefore, more work should be performed to reveal the systematic mechanism of how

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ultrasonic affects mass transport in a solid–liquid separation process. The effects of ultrasound on the pore size distribution inside a porous material are vital components of the systematic mechanism on ultrasonic enhanced dehydration.

The application of ultrasound in sludge treatment for improving sludge dewatering and degradation has been investigated in many literature reports, but most of the previous work primarily focused on the effects of the ultrasonic treatment on the sludge properties including floc size, filterability, settleability and bound water content [7–17]. However, little attention was paid to the pore size distribution characteristics inside a sludge subjected to sonication. In fact, the heat and mass transfer capacity of sludge largely depends on the sludge pore size distribution characteristics during the thermal drying process [27–29]. Therefore, to investigate the effect of ultrasonic pretreatment on the sludge thermal drying process, the transformation of the pore size distribution in a sludge undergoing ultrasonic irradiation is the most crucial problem to be considered. For this reason, our present work mainly focuses on the influences of the ultrasonic treatment on the pore size distribution in sludge.

However, the internal microscopic pore structure of sludge is complex and irregular, and traditional Euclidean geometry is unable to describe it appropriately. Fortunately, fractal geometry provides a new language in which previously intractable natural features can be described with more mathematical rigor. The fractal theory allows the characterization of objects in terms of their self-similar (scale invariant) properties [30]. Since the presentation of fractal theory by Mandelbrot, many scholars have shown considerable interest in the application of fractal geometry to characterize irregular or disordered objects in various subjects, such as porous media, roughness of surfaces, rocks and fractures, fractal aggregates, and granular materials [31–35]. Consequently, fractal theory could be a useful means for quantifying pore structure in sludge. Meanwhile, the heat and mass transport parameters of porous media, such as porosity, permeability, thermal conductivity, diffusion coefficient, etc., can be totally characterized by fractal dimensions. Yu and co-workers performed valuable work on the pore structure of porous media by means of fractal theory. They developed fractal permeability models for bi-dispersed porous media in both a saturated and an unsaturated state in terms of the tortuosity fractal dimension and the pore area fractal dimension [31]. Xu and Mujumdar presented a detailed review about the application of fractal theory on drying. They investigated the application of fractal theory on characterizing the microscopic and macroscopic structures of materials during drying and indicated that the fractal dimensions were used to quantify the structure changes of materials during drying [29]. Yiotis et al. performed two-dimensional pore network simulations of isothermal drying both in the presence and absence of gravity forces. They adopted the fractal dimensions to characterize the invading gaseous phase and the drying front perimeter [33]. The previous valuable investigations about applying fractal theory on quantifying the structure of porous materials and their drying processes laid a favorable theoretical foundation for our present work.

Therefore, the aim of the present work is to investigate the effect of ultrasound radiation on the pore size distribution inside active sludge. An experiment on the ultrasonic pretreatment of sludge was carried out, and the pore structures inside the sludge after the ultrasonic treatment with different acoustic energy densities and treatment times were observed using a microscope. The pore size distribution was characterized by fractal geometry, and surface fractal dimension was applied to qualify the change in pore size distribution in sludge under different operating condition of ultrasonic treatment. Finally, the evolution of the pore size distribution inside sludge under various sonication conditions was analyzed and discussed.

2. Materials and methods

2.1. Raw material and sample preparation

The activated sludge samples were collected from a municipal wastewater treatment plant (WWTP) in Nanjing, China. The moisture content of the activated sludge was approximately 87%. More than 30 sludge samples, each with a volume at 50 mL, were prepared in 100-ml beakers and stored at 4 °C.

2.2. Experimental setup

The experimental setup consisted of an ultrasonic treatment unit, a freeze-drying unit and a microscopic observation unit. A schematic of the experimental setup is depicted in Fig. 1. The two major components of the ultrasound unit were the acoustic generator and the transducer. The transducer converted electrical energy into mechanical vibration and amplified the vibration. In the present experiment, ultrasonic treatment unit (Xianou, Nanjing, China) provided an operating frequency of 20 kHz, and the ultrasonic power inputted in sludge sample was adjusted from 0 to 50 W. The ultrasonic transducer was equipped with a titanium alloy horn with a 16 mm tip diameter, and the maximum amplitude fitted the horn was about 50 μm. The freeze-drying equipment (LGJ-10D, Four-Ring Science, Beijing, China) consisted of a cold trap, vacuum drying chamber, control unit and vacuum pump. When the freeze-drying equipment was not loaded, the temperature of cold trap can reach less than −56 °C, and the limiting vacuum was less than 10 Pa. The microscope (OLYMPUS, Japan) was equipped with a CCD (charge-coupled device) microscope camera, which transformed the optical image signal into a digital signal and allowed the image to be stored in the computer.

2.3. Experimental procedure

Sludge samples (50 mL) were placed in a 100-mL beaker prior to sonication. The probe tip of ultrasonic transducer was immersed in

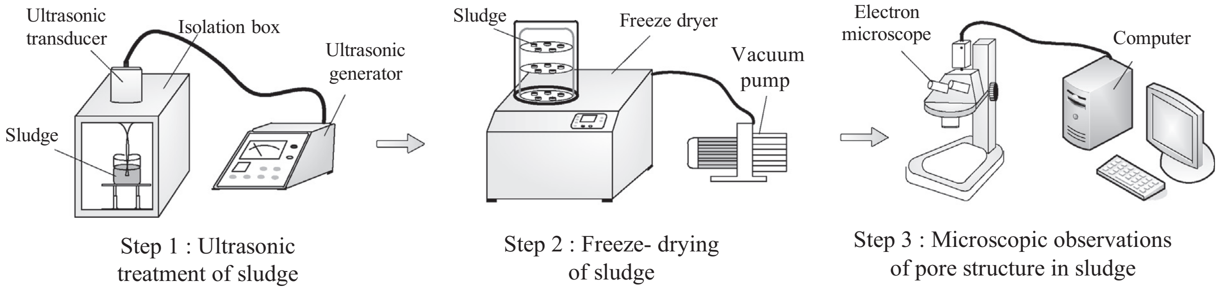

Fig. 1. A schematic diagram of the experimental setup for observing the pore structure inside the sludge under ultrasonic treatment.