Applied Thermal Engineering 91 (2015) 354–362

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Experimental and modeling study of the long cylindrical oily sludge drying process

Shuanghui Deng [a], Xuebin Wang [a, *], Houzhang Tan [a], Hrvoje Mikulčić [b], Zhifeng Li [a], Ruijie Cao [a], Zhao Wang [a], Milan Vujanović [b]

[a] MOE Key Laboratory of Thermo-Fluid Science and Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China
[b] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 10000 Zagreb, Croatia

HIGHLIGHTS

- The drying process of long cylindrical oily sludge was studied.
- A drying model was developed in Boltzmann form: $MR = A_1/(1 + e^{(t-k)/n})$.
- The developed model accurately predicted the drying process of oily sludge.

ARTICLE INFO

Article history:
Received 16 June 2015
Accepted 18 August 2015
Available online 29 August 2015

Keywords:
Experiment
Mathematical modeling
Oily sludge
Cylindrically shaped
Drying temperature
Boltzmann model

ABSTRACT

The drying of oily sludge is an essential preliminary step for further effective thermal utilization. In this paper the effects of different diameters (4–8 mm) and temperatures (105–250 °C) on the drying characteristics of long cylindrical oily sludge made by the sludge shaper were studied. The drying characteristics were studied in an electro-thermal constant-temperature dry box. Results indicate that an increase in temperature and a decrease in diameter accelerate the drying rate and shorten the drying time. After drying, fractures appeared in the solid skeleton of long cylindrical oily sludge, resulting in the production of smaller cylindrically-shaped particles. Besides the experimental analysis, a mathematical drying model was selected for such a long cylindrical oily sludge. Based on the obtained experimental data, a Boltzmann drying model was written in the following form: *MR* (moisture ratio) $= A_1/(1 + e^{(t-k)/n})$. The mathematical model can be used to predict accurately the drying process of the long cylindrical sludge in the temperature range of the experiment. The model can furthermore be used to develop more efficient sludge drying equipment.

1. Introduction

Currently the main sources of energy in the world are petroleum derived products [1]. During crude oil exploitation, processing operations and other chemical and industrial operations in refineries, a large quantity of oily sludge (or oil sludge) is generated [2]. It has been reported that more than 60 million tons of oily sludge is produced every year and more than 1 billion tons of oily sludge has been accumulated worldwide [3]. Because of differences in crude oil source, processing scheme, and other chemical and industrial operation in refineries, the oily content of oily sludge varies over a wide range. The heavier and lighter petroleum hydrocarbons and other organic compounds in oily sludge can be generally classified into four fractions, including nitrogen-, sulfur- and oxygen-containing compounds, aromatics, aliphatics, and asphaltenes [4]. Usually, oily sludge is composed of 8–10% asphaltenes, 28–31% aromatics, 40–52% alkanes, and 7–22.4% resins by mass [4]. In pyrolysis process, about 80% of total organic carbon content in oily sludge converted into hydrocarbons and an important hydrocarbon yield occurred at temperatures between 327 and 450 °C [5]. The separation of oil from oily sludge occurred from 460 to 650 °C [6]. Due to the increasing production quantity around the world and its hazardous nature, oily sludge has become the center of a major research effort in terms of effective remediation [7].

Oily sludge is a complex mixture that contains large quantities of water, various petroleum hydrocarbons, heavy metals and solid

* Corresponding author. Tel.: +86 029 82667723; fax: +86 029 82668703.
E-mail address: wxb005@mail.xjtu.edu.cn (X. Wang).

http://dx.doi.org/10.1016/j.applthermaleng.2015.08.054
1359-4311/

particles [8]. With the exploration and development of oilfields, the increasing amount of oily sludge aggravates the environmental pollution. Due to the rising energy costs and because environmental impact become of great concern worldwide, reducing the toxicity of oil sludge, and recovering oil by removing water and solids is receiving increased attention [9]. Following this statement, removing of water from oily sludge is as important as dewatering (or drying) of sewage sludge [10,11]. Industries currently use expensive centrifuge and filtration operations as well as heat and chemical treatments to dry oily sludge and other waste materials. High water content is the primary problem for sludge further treatment and disposal [12]. Drying is often a necessary step during the process of sludge treatment. It largely reduces the moisture content, and increases the calorific value of the sludge. Dried sludge lowers costs in transporting and storage and is used as acceptable combustible materials [13]. The methods currently used to dry sludge include conductive heat transfer inside a screw dryer, and convective heat transfer directly from the hot gas [14]. During the air drying process, water from sludge is primarily removed by air convection, and free water mainly evaporates [15]. The main mechanism of water removal is convective evaporation [16]. In literature different factors that affect the drying kinetics of sludge, such as drying air temperature, velocity and different additive agents were investigated and reported [17–19]. These studies showed that the drying of sludge is a complex process, and that further research is needed in this field.

There are three distinct contents in the oily sludge. These are the oil, water, and solid content. It was reported that the oil represents 8–15%, the moisture 70–90%, and the solid represents 4–15% content of the oily sludge [20]. Due to this reason it is not easy to designing an effective thermal dryer of sludge largely due to the complex drying mechanisms and complicated structures of sludge [21,22]. Therefore sludge shapes and simulation models are of great importance in design, construction and operation of drying systems.

Many researchers focused their efforts on the study of the drying characteristics and mathematical model of sludge. Ruiz and Wisniewski [23] performed laboratory drying experiments of sewage sludge in stationary atmosphere at a temperature of 30 °C. The study presented the relationships between the hydro-textural characteristics of the sludge, and predicted the sludge behavior during drying according to its characteristics. Reyes et al. [24] determined drying kinetics of sewage sludge in a laboratory drying tunnel with parallel airflow at different temperatures. The study showed that the developed two-period model could be used to simulate the entire drying process and to predict temperature and air velocity during the drying process. Arlabosse et al. [25] designed a set of laboratory scale experimental techniques and developed a simple model of the continuous industrial dryer. The model predictions showed good agreement with the reported experimental data. However, only few studies investigated the influence of shaped sludge on the drying process. Shaped sludge contributes to the sludge volume reduction, improves the efficiency of water evaporation, and reduces the energy loses [26].

Currently, there are only few research studies on the drying characteristics and mathematical modeling of the long cylindrical oily sludge at low drying temperatures. The objective of the present study was to experimentally investigate the air drying behavior of the long cylindrical oily sludge at different drying temperatures and of different diameters. Also, in this study, according to the experimental observations, a predictive mathematical model of the long cylindrical oily sludge drying process is to developed. The obtained results, both experimental and mathematical, are of great importance in the effective design and the final adjustment and installation of the sludge drying equipment.

2. Materials and methods

2.1. Materials

Oily sludge analyzed in this study was obtained from Sinopec Luoyang Company in Luoyang city, Henan Province, China. The initial water and oil content for studied oily sludge sample were 89.9% and 7.55%, respectively. Oily sludge was thoroughly dried in the oven at 105 °C until its mass did not change. After milling and sieving into 50–200 μm in diameter, dried oily sludge was dried again in the oven at a constant temperature of 105 °C for 24 h. The ultimate and proximate analysis of dried oily sludge is shown in Table 1. In Table 1, "C_{ad}", "H_{ad}", "O_{ad}", "N_{ad}" and "S_{ad}" denote carbon content, hydrogen content, oxygen content, nitrogen content and sulfur content as air dried basis respectively. "M_{ad}", "V_{ad}", "FC_{ad}" and "A_{ad}" denote moisture content, volatile content, fixed carbon content and ash content as air dried basis respectively. As can be seen dried oily sludge has a significant heating value. During each forming process of oily sludge, the same amount of sludge was weighed to ensure the same stack height of oily sludge in the sludge shaper. We drove the screw arbor to extrude the long cylindrical oily sludge samples with different diameters using shaper plates of different size. The long cylindrical oily sludge samples with different diameters (Φ4mm × 100 mm, Φ6mm × 100 mm and Φ8mm × 100 mm) were obtained by the sludge shaper. The initial masses of the long cylindrical oily sludge samples with Φ4mm × 100 mm, Φ6mm × 100 mm and Φ8mm × 100 mm in drying experiments by hot air were 1.00 g, 2.50 g, and 4.50 g respectively. The maximum deviation of the initial mass of each sludge sample was controlled under 0.01 g. The schematic figure of the long cylindrical sludge shaper is shown in Fig. 1.

2.2. Experimental procedures

The experimental apparatus of sludge drying is shown in Fig. 2. The drying experiments were conducted in an electro-thermal constant-temperature dry box with different air temperatures. When the temperature of the dry box reached the set temperature, the prepared sludge sample on the aperture tray was introduced into the dry box. The drying process started once the sample hung on the peg of the automatic analytical balance. At the same time, the weight change of the sludge sample was monitored online by the computer monitoring software.

2.3. Evaluation indexes of drying

The wet basis moisture ratio of the long cylindrical oily sludge during the drying process was calculated using the following expression:

$$MR = \frac{m_t - m_\infty}{m_t}, \tag{1}$$

where m_t is the sample weight at time t, and m_∞ is the dry weight of the sample both in g.

The drying rate of the long cylindrical oily sludge can be expressed as:

$$Drying\ rate = \frac{MR_{t+dt} - MR_t}{dt}, \tag{2}$$

here the drying rate is expressed in min^{-1}.