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Comparative approach to the performance of direct and indirect solar drying of sludge from sewage plants, experimental and theoretical evaluation

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ABSTRACT

The objective of this work is to contribute to the enhancement of sludge of wastewater treatment plants and solar energy in Algeria. A kinetic comparison was made to the direct and indirect solar dryers operated with natural convection. Two models have been developed to simulate drying. Under natural conditions and at ambient temperatures below 32 °C, the indirect dryer gives high temperatures and efficiency compared to the direct dryer. Drying curves show that the higher the temperature is, the shorter drying time is and the faster drying speed is. From the drying curves, only the decreasing speed phase or slowdown (phase 2) is observed in the two types of drying, which is similar to results obtained in the literature with plant products. Solar dryers have reduced the time needed, a moisture reduction of 71% which increases the dryness of the mud from 14.47% to 85.53%. Thirteen mathematical models existing in the literature were tested and compared with the proposed models. The proposed models and the modified Henderson and Pabis model showed the best smoothing qualities of all indirect and direct dryer drying kinetics, with an advantage for the proposed models as they are dimensionless (independent models of units of measurement), they contain fewer parameters and verify the boundary conditions.

1. Introduction

Today, more than ever, waste management has become a priority of the environmental policy in the world (Hort et al., 2009). Wastewater from various urban activities cannot be rejected as such in the environment because it contains various organic and inorganic pollutants. They must undergo, before their release into the natural environment, a sewage treatment which leads the production of sludge (Roux et al., 2010). The sludge purification plants are considered as waste by several regulations. They are a bulky waste (95–99% water) whose composition is problematic: highly fermentable substances and high disease burden (viruses, bacteria, parasites, etc.) (Gavala et al., 2003).

In Algeria, the volume of wastewater discharged nationwide is currently estimated at nearly 750 million m^3 and will exceed 1.5 billion m^3 by 2020. The current situation (operation) number of wastewater treatment plant is 102 (52 PLANTS + 50 lagoons), current installed capacity is 570 h m^3/year (1999: 28 PLANTS to a processing capacity of 98 million m^3/day). Location of being implemented program: number of wastewater treatment plants is 176 (87 PLANT + 89 lagoons), installed capacity is 355 h m^3/year (Kessira, 2013). The problem of disposal of sludge from sewage treatment plants is more delicate given the increased production of wastewater and regulations that is becoming more demanding. The use of sewage sludge in agriculture has been widely practiced in most developed countries (Laube and Vonplon, 2004). Sludge processing pathways have always had goals; reduction of volume and fermentability, namely their stabilization (Bennouna and Kehal, 2001). In this perspective, the drying is often a necessary plant to facilitate subsequent management of sludge as recovery or storage (Rayan, 2007).

There are several methods for sludge dewatering, among which mentioned is mechanical dewatering and thermal drying. The latter will be a development because it is the one that was chosen as part of this work. Drying is a dewatering method for the extraction of a solid, a semi-solid or a liquid by evaporation (Al-Masri and Kahline, 2013). The dryers are different because of the energy source that can be used as a fossil fuel, gas, electricity or solar power and the nature of the transfer of heat that is transmitted to the product (Fohr and Figueiredo, 1987; Lahsasni et al., 2004). Energy has always been a vital issue for humans and human societies. Human behavior is strongly induced by the availability or non-availability, abundance or its scarcity. These behaviors will arise new challenges, particularly in the environment and the socio-economic balance (Bekkouche, 2009; Angélique, 2002).

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Nomenclature

DM	dry matter (%)
DSD	direct solar dryer
ISD	indirect solar dryer
m_e	the mass of the empty dish or crucible in grams
m_f	the mass of the dish or crucible containing the sample in grams
m_o	the mass of the dish or crucible containing the dry matter in grams
r^2	correlation coefficients
RMSE	root mean square error
WM	wet matter (%)
X	moisture content at any time of drying (kg water/kg dry matter)
X_e	equilibrium moisture content (kg water/kg dry matter)
X_0	initial moisture content (kg water/kg dry matter)
X_r	reduced moisture ratio (kg water/kg dry matter)
χ^2	reduced chi-square
$-dX/dt$	drying rate at any time of drying (kg water/(kg dry matter. min))

Renewable energy has been a first phase of development on the occasion of the oil shocks of 1973 and 1978 and a downturn after the against-shock of 1986, before finding a second breath in 1998 following the signing of the Kyoto Protocol; a protocol which provides for an 5.2% decrease in gas emissions greenhouse of rich countries over the period 2002–2012 compared to 1990 (Bekkouche, 2009; Rakotondramiarana et al., 2005). Solar energy is a viable alternative for developing countries as Algeria. The use of this renewable energy can meet the drying process in the interests of sustainable development.

It should indeed be known that Algeria belongs to the regions located in the Sunbelt of northern Africa, southwestern United States of America and Australia. These regions have the highest solar deposits in the world. For Algeria, the duration of exposure on almost all the national territory exceeds 2000 h annually and reaches 3900 h (Highlands and Sahara). The daily-gained energy on a horizontal surface of 1 m^2 is about 5 KWh in most of the country, nearly 1700 KWh in the north and it is 2263 KWh in the south a year (Benlahmidi, 2013; Sabri and Desmons, 2005; Schimmerling et al., 1998).

Open air sun drying is the dominant method that is used to dry mud in which the sludge is directly exposed to solar radiations in an open environment, which generates bad odors. Hence, the idea is of drying the mud in solar dryers. Covered solar drying gave better results than open solar drying (Bennamoun, 2012). In the solar drying there are two modes according to the bibliographic data: it is direct drying when the material to be dried directly receives solar energy, and it is indirect drying when solar energy is captured by a device called a solar collector, generally allows preheat the air which is then sent to the products to be dried (Fohr and Figueiredo, 1987; Bekkouche, 2009).

In Algeria, as in different countries, the solar drying is still at the experimental stage. To that end, our work is a contribution to a better understanding of solar sludge drying by direct and indirect means. The literature is scarce on the solar drying kinetics of mud. Solar drying facilities dedicated to sewage sludge remain a novelty. Their specificity is the high dependence on operating parameters on local weather conditions (Krawczyk, 2016). The majority of sludge drying studies was carried out in autoclaves at high temperatures ranging from 70 °C to 200 °C, as the work of Bougrier et al. (2008) and Bennamoun et al. (2015) states. At air temperatures varying between 80 °C and 200 °C, Bennamoun et al. (2015) observed three main phases of drying during the drying of the sludge bed. These phases are reduced to only two for small samples. All comparisons that have been made between direct and indirect solar dryers are done on plant or food products. Sallam et al. (2013) found that direct solar drying with natural convection of mint is more efficient than indirect drying at ambient temperatures above 32 °C. Several researches have investigated the drying kinetics of food products and evaluated various mathematical models to describe the drying characteristics (El-Sebaii and Shalaby, 2013; Boudhrioua et al., 2007), but they have not studied the solar drying kinetics, with natural convection of the sludge from sewage treatment plants. As mentioned above, the literature is scarce on the kinetics of solar drying of mud. Moreover, most previous studies used forced convection dryers. So, this study was carried out to study the drying kinetics of mud as a product using pilot scale solar dryers considering the effect of solar dryer type (direct and indirect) operating in natural convection .

A theoretical study was provided with the proposal of two new universal dimensionless models. The experimental results will undergo a mathematical modeling (thanks to the proposed models and thirteen models existing in the literature) which allows to simulate the operation of each type of dryers (direct solar drier, indirect solar dryer), and to predict the model of dryer achieving the best performances. We shall conclude with a comparison between the theoretical and experimental results, between the proposed models and those of the literature, in addition to a general comparison between direct and indirect solar drying.

2. Materials and methods

Two drying methods have been carried out to develop a dehydrated sludge from a wastewater treatment plant (WTP) in the wilaya of Boumerdes. Solar dryers, in Fig. 1 (a, b), have been designed and made

(a) (b)

Fig. 1. Solar dryers: (a) DSD; (b) ISD.