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Forced Convective Drying of Wastewater Sludge with Presentation of Exergy Analysis of the Dryer

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Abstract

The main objective is studying the fundamental aspect, by the mean of the drying kinetics, the application of forced convective drying of wastewater sludge with determination of the optimum drying conditions. The drying system is composed of two units; small samples of 2.5 g are dried in the first unit and bed of sludge weighting 250 g is dried the second unit. The experiments are performed under air temperatures varying between 80°C and 200°C. The range of the air velocity and its humidity is 1- 2 m/s and 0.005- 0.05 $kg_{water}/kg_{dry\ air}$, respectively. The experiments are performed for two different sludges; activated sludge (AS) and thermalized and digested sludge (TDS). Usually, three main drying phases are observed during drying of bed of sludge. These phases are reduced to only two for small samples. Determination of the influent parameters shows that temperature of the drying air and sludge origin can profoundly influence the drying kinetic of the sludge. The exergy analysis of the two units of the drying system allows selecting 140 °C, 2 m/s, 0.05 $kg_{water}/kg_{dry\ air}$ as optimum drying condition with an exergy efficiency reaching 90%.

KEYWORDS: Micro-dryer, bed dryer, sludge origin, drying conditions

NOMENCLATURE

A	area (m^2)
Cp	specific heat (J/kg.K)
E	emissive power (W/m^2)
F	shape factor
g	gravitational acceleration (m/s^2)
g_c	constant in Newton's law
J	Joule constant
m	mass flow rate (kg/s)
N	number of species
P	pressure (kPa)
s	specific entropy (kJ/kg.K)
T	temperature (K or °C)
u	specific internal energy (kJ/s)
V	velocity (m/s)
v	specific volume (m^3/kg)
vol	volume (m^3)

z	altitude (m)

Greek symbols

φ	Exergy efficiency
μ	chemical potential (kJ/kg)

Subscripts

a	air
i	inlet
0	reference or initial
∞	ambient

INTRODUCTION

New published scientific papers confirm that the production of wastewater sludge is still increasing for the next years. The most important producers in the world are the European Union, China and U.S with an estimated total production of 11.7 million tons, 9.18 million tons and 8 million tons of dry solids, respectively (Bennamoun, Léonard and Arlabosse 2013; Bennamoun 2012a). Managing these huge quantities of sludge is presenting real issues. The physico-chemical studies of the wastewater sludge revealed the existence of attractive components, such as manganese, zinc and iron that can be exploited in agriculture. In addition, wastewater sludge can be considered as a non-neglected source of nitrogen, carbon, phosphorus and other components that can be valuable (Bennamoun, Léonard and Arlabosse 2013). Hazardous components, such as mercury and arsenic, are also present and their removal before the use of the sludge in agriculture is compulsory. Usually, the water existing in the sludge is considered as a non-profitable element that causes the increase of handling, storage and transportation costs. The dried wastewater sludge can also be used in incineration as a source of energy with high calorific value.

As it is perceived drying is an inevitable process to add value to the wastewater sludge. Nowadays, mainly three technologies are used; radiation, conductive and convective drying. Microwave and solar energy are the two available processes to dry the wastewater sludge using radiation. However, the two techniques are still under intensive research and few works are published in this area (Bennamoun 2012a; Léonard et al. 2002; Salihoglu, Pinarli and Salihoglu 2007; Slim, Zoughaib and Clodic 2008; Mathioudakis et al. 2013; Domingez et al. 2004, Fang et al. 2013). This method presents a complicated technology that slow down its use at the industrial scale. Also drying wastewater sludge using solar energy is considered as time consuming process and highly depending on the weather conditions. Conductive drying of wastewater sludge was extensively explored by Ferasse, Arlabosse and Lecompte (2002), Deng et al. (2009 a,b), Yan et al. (2009), Arlabosse and Chitu (2007). They were able to study the fundamental behaviour and the variation of the drying kinetics of wastewater sludge during application of conductive drying. The temperature of the heated container, the speed of the agitator and the pressure applied were the main influent drying parameters. Usually, conductive drying presents several disadvantages, such as the non-practical design of the dryer and the long time needed for the accomplishment of the process (Bennamoun, Léonard and Arlabosse 2013). The most common method used in industry is convective drying; it presents generally a simple design of the system that makes easy the handling of the material and maintenance of the drying system. On the other hand, in comparison with conductive drying, the drying time of convective drying is always shorter. Léonard et al. (2002), Léonard et al. (2005), Léonard et al. (2008), Tao, Peng and Lee (2005, 2006) exhaustively studied the fundamental aspects of the wastewater sludge during convective drying with determination of the influent parameters. The temperature of the air, its velocity and humidity were the most influent parameters that have an effect on the performances of the process. It was found that origin of the sludge can also affect the experimental results (Léonard et al. 2004). Commonly, application of convective drying of wastewater sludge, without prior determination of the optimum drying conditions can lead to have a non-efficient process, and a non-homogeneous dried material with formation of a skin and apparition of cracks (Bennamoun, Léonard and Arlabosse 2013, Bennamoun 2012a, Tao, Peng and Lee 2005, Tao, Peng and Lee 2008, Bennamoun, Crine and Léonard 2013, Bennamoun, Fraikin and Léonard 2014, Font, Gomez-Rico and Fullana 2011).

The aim of this work is to study the performances of a pilot scale dryer, working in forced convection mode with application of several operating conditions and different wastewater sludge. The study contains two aspects: the fundamental aspect which is related to the drying kinetics of the sludge. However, the second aspect of the work is to study the exergy aspect of the two units of the drying system.

MATERIALS AND METHODS

Materials

Two sorts of sludge are tested; activated sludge (AS) collected in a wastewater treatment plant (WWTP) situated is Grosses Battes in Liège, Belgium. The second sludge is a thermolyzed and digested sludge TDS collected in a WWTP in Bruxelles-Nord, Brussels, Belgium. Water to be purified undertakes a primary treatment, an anaerobic phase and an alternating aerobic/anoxic phase to produce AS. Finally, phosphate is precipitated by ion chloride and biomass in excess is dewatered using a belt filter. AS is collected after application of a mechanical dewatering that gives the sample an initial dry matter of around 14.5%. TDS undergoes the same treatments except for dehydration which is carried out by centrifugation. Subsequently, TDS is subject to a temperature of 160 °C and a pressure of 6 bars for 30 minutes. The sludge is then flashed and digested to produce biogas. Before the use of the wastewater sludge and application of drying process, the material is kept refrigerated at 4 °C until its use. Table 1 shows several properties of the two tested materials.

Pilot Scale Dryer

The pilot scale dryer is constituted of two units. The first unit is represented in Figure 1. Before performing drying with this unit also called micro-dryer, the sample was extruded in a cylindrical shape that has almost equal diameter and height of about 15 mm. This part of the drier is equipped with a surface camera to follow the variation of the volume and surface of the samples during application of the process. It is equipped, as well, with an infrared pyrometer which gives the surface temperature of the sample. The second part of the dryer allows drying a bed of wastewater sludge with a maximum initial weight of about 300 g. Figure 2 represents the second part of the convective dryer. The control system of this part allows governing the temperature of the heated air, its velocity and humidity. The tested material is introduced in a perforated tray which allows the flow of the air within the sludge. The temperature of the product can be taken in three different heights of the bed. The system was dotted with sensors in order to register the quantity of gaseous emissions during convective drying of wastewater sludge. However we will focus in this work on just the variation of the mass and temperature of the samples.

EXERGY ANALYSIS

As reported by Prommas, Rattanadecho and Jindarat (2012), Prommas, Keangin and Rattanadecho (2010), Prommas, Rattanadecho and cholaseuk (2010), the second law of thermodynamics introduces the useful concept of exergy in the analysis of thermal system. Exergy analysis evaluates the available energy at different points in a system. Exergy is a measurement of the quality or grade of energy that can be destroyed in the thermal system. The second law states that the part of exergy entering a thermal system is destroyed within the system due to the irreversibility. The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems usually represented by the following equation (Chowdhury, Bala and Haque, 2011):

$$\begin{aligned}\mathrm{Exergy} &= (\mathrm{u}_0-\mathrm{u}_\infty)-\mathrm{T}_\infty(\mathrm{s}-\mathrm{s}_\infty)\mathrm{N}+\frac{\mathrm{r}_\infty}{\mathrm{J}}(\nu_0-\nu_\infty)+\frac{\nu}{2\mathrm{gJ}}+\\ &(\mathrm{z}-\mathrm{z}_0)\frac{\mathrm{y}}{\mathrm{gcJ}}+\sum\nolimits_{\mathrm{c}}(\mu_\mathrm{c}-\mu_\infty)\mathrm{N}_\mathrm{c}+\mathrm{E}_\mathrm{i}\mathrm{A}_\mathrm{i}\mathrm{F}_\mathrm{i}(3\mathrm{T}^4-\mathrm{T}_\infty{}^4-4\mathrm{T}_\infty\mathrm{T}^3)\end{aligned} \tag{1}$$

The right side of the equation are representing respectively (from the left to the right) the internal energy, the entropy, the work, the momentum, the gravity, chemical reaction and radiation emission. In our studied cases, the predominant energy is the entropy part and its exergy can be written under the following form (Akyol, Akan and Durak, 2015, Aviara et al. 2014):

$$\mathrm{Exergy} = \mathrm{m_a Cp_a} \,|\, (\mathrm{T} - \mathrm{T_\infty}) - \mathrm{T_\infty} \ln \frac{\mathrm{r}}{\mathrm{m}} \,| \qquad (2)$$

The exergy efficiency of the drying system can then be calculated based on the application of the exergy balance between the inlet air that flows inside the drying chamber and the outlet air (Bennamoun 2012b, Akyol, Akan and Durak, 2015, Aviara et al. 2014) represented by:

$$\varphi = \frac{Exergy_{inlet} - Exergy_{loss}}{Exergy_{inlet}} = \frac{Exergy_{outlet}}{Exergy_{inlet}} \qquad (3)$$

RESULTS AND DISCUSSION

Forced convective drying is performed under the conditions shown in Table 2, applied for three sorts of experiments. The two first experiments are performed with the micro-dryer (Figure 1). AS and TDS sludge were tested by using small samples having an initial mass of 2.5 g. The experiments will be noted respectively AS1 and TDS2. During the third experiment noted AS3; 250g of AS are introduced in a bed and dried using the second unit of the dryer (Figure 2). Based on the official methods determination of the initial moisture was obtained by inserting a mass of the tested material in an oven under 105°C until the sample mass becomes constant. The initial moisture content can be then easily determined. The results show that the initial moisture of AS1 and AS3 changed from 2.05 kg/kg to 2.19 kg/kg calculated in dry basis. The initial moisture content is 4.97 kg/kg dry basis for TDS2.

Fundamental Results Of Application Of Forced Convective Drying Of Wastewater Sludge

Figure 3 shows the drying kinetic of AS1 and TDS2 during convective drying performed under COND1.

Contrary to other studies (Léonard et al. 2002, Léonard et al. 2003), the figure shows the existence of mainly two phases for both tested sludge; a short adaptation phase and a falling drying rate period. The adaptation phase represents the first reaction of the material to the application of the drying conditions. Commonly, it is distinguished by an important increase of the drying rate versus a small decrease in the moisture content of the material. At the end of this phase the maximum value of the drying rate is reached. After that the drying rate starts decreasing until the end of the process. Figure 3 shows, as well, that the origin of the sludge can play an important role on its behaviour, as we can see that the maximum value of the drying rate of the TDS2 is more important than AS1. This difference is probably due to quantity of moisture contained in TDS2, which is more important than in AS1. These observations are with agreement with other experimental results (Léonard et al. 2004, Bennamoun, Fraikin and Léonard 2014). It is important to attract the attention that during convective drying of the two sludges it was possible to register all the changes in volume and surface of the samples. The results show that shrinkage is happening and varying linearly with the moisture content of the materials (Bennamoun et al. 2013). Shrinkage of TDS2 was more important than AS1 and at the end of the process the volume of TDS2 was 37% of its initial volume against 55% for AS1 (Bennamoun et al. 2013), as it is indicated in Table 1. In the case, the volume of the samples changes, such as for shrinkage during drying of wastewater sludge, it is more accurate to represent the drying rate or the flux per unit of surface (Bennamoun, Crine and Léonard 2013, Bennamoun, Fraikin and Léonard 2014, Bennamoun et al. 2013), as it is shown in Figure 3.

Figure 4 shows a different behaviour of the bed sludge drying kinetic, comparing to the small sample, with appearance of almost a constant phase before the falling drying rate phase. The influence of the drying conditions is shown in the figure, as well. The increase of the drying air temperature causes the increase of the flux. However, almost the same results are obtained for (140°C, 2 m/s) and (200°C, 1 m/s). On the other hand, the maximum value of the drying rate was more important during application of COND2 than the other operating conditions. This difference slightly decreased with the moisture decrese. Similar results and observations were obtained by Bennamoun, Crine and Léonard (2013), during forced convective drying of a small sample of wastewater sludge. The second unit of the dryer, related to dry a bed of sludge, is not equipped with camera. Accordingly, it was not possible to follow the variation of the volume and the surface during the process. This reason pushes us to make the graphical presentation of the drying rate without including the change of the surface (drying rate give in g/min).

Figure 5 shows the evolution of the temperature of wastewater sludge AS1 and AS3 during forced convective drying. The figure shows that drying a small sample of 2.5 g (AS1) has a different behaviour comparing to bed drying (AS3). Mainly, the energy, used to dry samples using AS1 condition, is used at the same time for removing the water of the product and to increase its temperature. Similar results were obtained by Bennamoun, Crine and Léonard (2013) and Bennamoun et al. (2013). However, following the temperature of the bed of sludge shows different behaviour and confirms the results obtained in Figure 4 with the existence of a constant drying rate phase. Accordingly, the temperature of the sample passes by three phases. Adaptation phase is the first observed phase, during this phase the product adapts itself to the applied drying conditions and the energy serves essentially to heat-up the product. T1, T2 and T3 represent respectively the product temperatures at h/4, h/2 and 3h/4, where h is the height of the bed. The figure shows that during the adaptation phase there is no difference between the different heights of the bed. After this phase, the temperature of the product shows a constant profile (representing the constant drying rate phase). At this stage, the acquired energy is used for just evaporation of the moisture of the tested sample. Figure 5 shows that drying is performed with a non-homogenous manner as sludge at h/4 takes shorter time than h/2 and 3h/4. Similarly, the constant drying rate phase is accordingly shorter for h/4 than other heights. In the falling drying rate phase, the energy is serving for the evaporation of the product moisture and the increase of its temperature. The temperature of the product is then increasing until reaching the temperature of the drying air temperature. Furthermore, the figure shows that drying time of AS3 is longer than AS1 and this is probably due to the initial mass, as increasing the quantity of the samples leads to the increase of the drying time, as confirmed by the work published by Bennamoun and Belhamri (2003), dealing with forced convective drying of food stuffs.

Exergy Analysis Of The Pilot Scale Convection Dryer

Figure 6 shows the variation of the exergy efficiency of the drying system during forced convective drying of wastewater sludge. It shows that the general tendency of the exergy is to increase with drying time with a certain constant part probably corresponding to the constant drying rate phase. Exergy efficiency gives an idea about how much energy is used to perform the process. The figure confirms that increasing the temperature of the drying air, in order to have a shorter drying time, does not include assuredly that the process is efficient. It is clearly shown that application of COND2 was more efficient than the other operating conditions COND1 and COND3. Operating with COND2 allows having a better use of the energy to perform drying process with an efficiency varying from 70 to 90%. For COND1, the efficiency was not high, which means that the energy loss is important; the exergy efficiency varies from 60 to around 80%. For COND3, 200 minutes were necessary to attain an exergy efficiency of 85%. Similar tendency of the presented results were obtained by Prommas, Rattanadecho and Jindarat (2012), Prommas, Keangin and Rattanadecho (2010), Prommas, Rattanadecho and cholaseuk (2010) during performing forced convective drying of different materials inserted in thin and bed layers.

Figures 7a and 7b show the variation of the exergy efficiency during forced convective drying of wastewater sludge AS1 and TDS2. The figures show similar behaviour. The performances during application of COND3 are not considerably good as the exergy efficiency is decreasing with time. Contrary, the application of COND1 and COND 2 shows an increase in the exergy efficiency nevertheless the performances of COND2 were better than the others, as the efficiency varies from 85 to 90% for both sludges AS1 and TDS2. The comparison of the obtained optimum operating conditions represented by COND2 for AS1 and TDS2 shows that the exergy efficiency for AS1 is slightly better, which means that the origin of the sludge can also influence the performances of the dryer and its exergy efficiency.

CONCLUSION

Such pilot scale drying system, dotted with two different drying systems, one for small 2.5 g samples and the other for bed layers of 250 g, allows having and comparing fundamental results related to forced convective drying of different sorts of wastewater sludges. During bed layers drying, the material passes through three phases; adaptations phase, constant drying rate phase and falling drying rate phase. The constant drying rate phase is missed during drying of samples of 2.5 g and mainly two phases can be observed; the adaption phase and the falling drying rate phase. The recorded sample temperature confirms the previous observations and the different phases for both cases.

The drying air temperature and the origin of the sludge can be presented as important parameters that highly influence the behaviour of the drying kinetic of the wastewater sludge during forced convective drying.

The exergy study of the drying systems shows different behaviour of the two units of the drying system with better results obtained at the application of the following conditions: drying air temperature of 140°C with air velocity of 2 m/s and a humidity of 0.05 kg water/kg dry air, for both sludge with an exergy efficiency reaching 90%.

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Table 1. Information related to the tested wastewater sludge

	AS	TDS
Origin	Grosses Battes (Liege, Belgium)	Bruxelles-Nord (Brussels, Belgium)
Population-Equivalent	59000	1400000
Mechanical dewatering system	Belt filter	Centrifuge
Dry matter (%)	17	31
Volatile compound (%)	64	46
Initial moisture content (kg/kg dry basis)	2.05-2.19	4.97
Final volume after drying (small samples)	0.55 $(\mathrm{vol})_0$	0.37 $(\mathrm{vol})_0$

Table 2. Operating drying conditions

Noted conditions	Temperature (°C)	Velocity (m/s)	Humidity (kg $_{\text{water}}$/kg $_{\text{dry air}}$)
COND 1	200	1	0.005
COND 2	140	2	0.050
COND 3	80	1	0.005

Figure 1. Simplified schema of the first part of the dryer

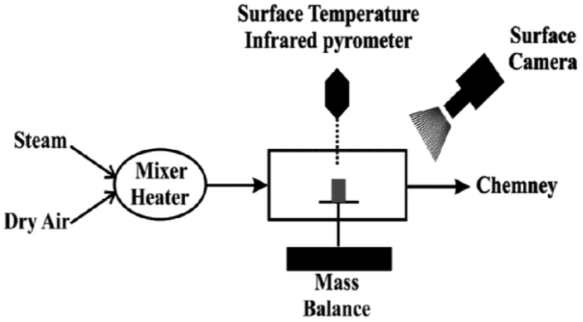


Figure 2. Simplified schema of the second part of the dryer (Fraikin et al., 2011).

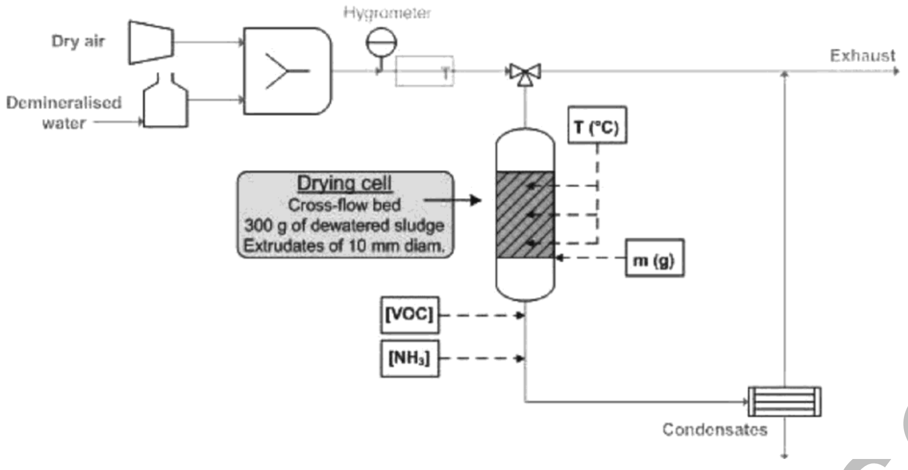


Figure 3. Influence of the sludge origin on the behaviour of the drying kinetic

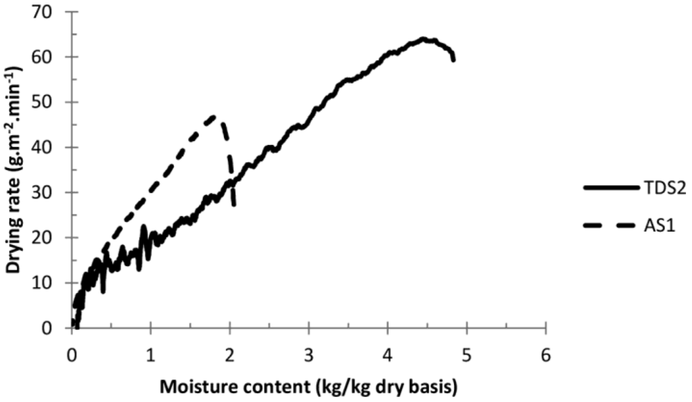


Figure 4. Influence of the operating drying conditions on the behaviour of the drying kinetic for AS3

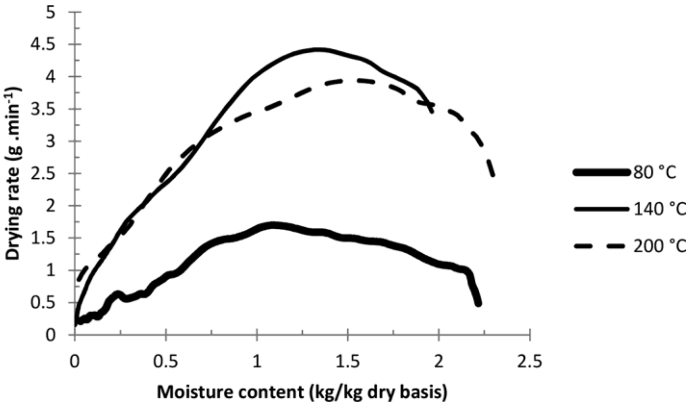


Figure 5. Registered product temperature during convective drying of AS1 and AS3

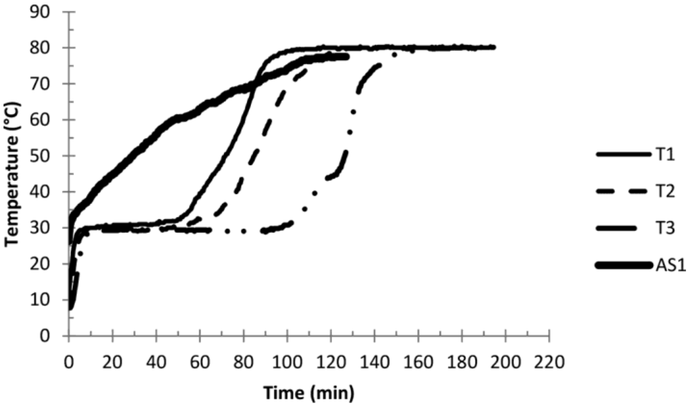


Figure 6. Exergy efficiency during forced convection bed drying of wastewater sludge

AS3

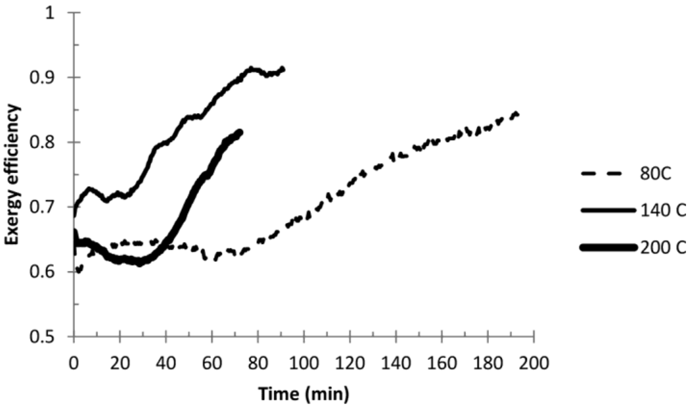
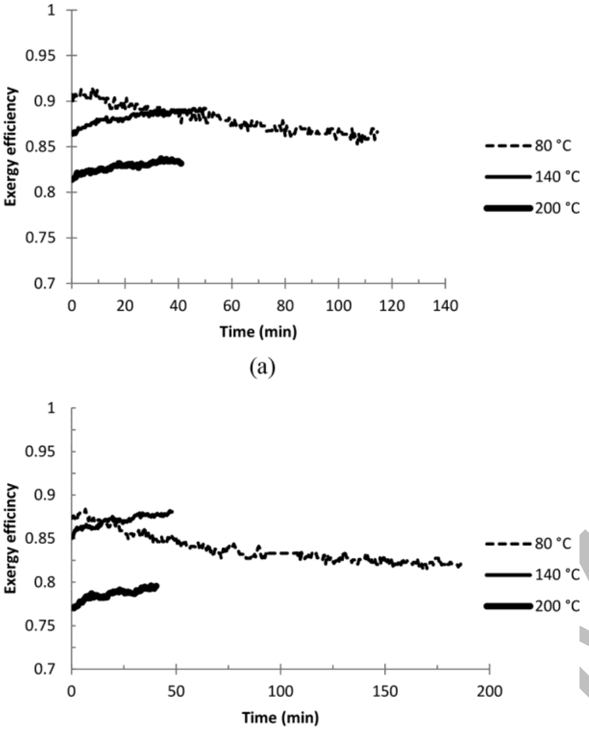


Figure 7 a. Exergy efficiency of the drying system during forced convection drying of AS1 Figure 7 b. Exergy efficiency of the drying system during forced convection drying of TDS2



(a)

(b)