CONTRIBUTION TO THE MODELLING OF WASTEWATER SLUDGE DRYING KINETICS: STUDY OF THE OPERATING CONDITIONS EFFECT

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Abstract: This work concerns the influence of the operating conditions on sludge drying kinetics. The drying experiments were carried out in a discontinuous pilot scale convective belt dryer. For each experiment 1 kg of wet material extruded in 12 mm diameter cylinders was used. The effect of the drying temperature (120, 140 and 160°C), described as the most influent operating condition, is investigated. Also, several mathematical models, reproducing the experimental results, are evaluated. Page model and the 4th degree polynomial model describe well the obtained results with correlation coefficients close to 1 and standard errors varying from 0.0029 to 0.0097.

Keywords: Sludge, Convective drying, temperature effect, Page model, 4th degree polynomial model

INTRODUCTION

The increase of food and energy demand is one of the consequences of, in one hand, growing of the world population and, on the other hand, working on having more facilities and life amelioration and accommodation. Unfortunately, it has not only good effects; it leads to the increase of food and energy prices but also to the augmentation of domestic, commercial and industrial wastes. We give a particular attention to the sludges generated from wastewater treatment, whose management has become a real challenge.

Early and anxious of the situation, the European Union has encouraged and put directives concerning the wastewater treatment and landfilling of biodegradable materials (Conseil de l'Union Européenne, 1999, 1991). Nowadays, Europe produces annualy almost 15 million tons of sludge expressed on dry basis and the two major issues are agricultural and thermal valorization. In both cases, drying constitutes a critical pretreatment after mechanical dewatering. It can indeed reduce the water content below 5% dry solids. This obviously reduces the mass and volume of waste and, consequently, the cost for storage, handling and transport. Moreover, the removal of water to such a low level increases drastically the lower calorific value, transforming the sludge into an acceptable combustible.

Due to the importance of the treated problem and its effect on the environment, the tentative of the Scientifics to resolve the problem is growing; several works are dealing with drying and thermal processing of sewage, municipal and residual sludges (Smollen, 1990, Grüter et al., 1990, Gross, 1993, Kazakura and Hasatani, 1996, Vaxelaire and Puiggali, 2002 and Chen et al., 2002). In order to know more about the behavior of the sludges during drying process, other Scientifics have used the X-ray microtomography method (Léonard et al., 2002, 2005a, 2005b), which has allowed following shrinkage (Léonard et al., 2004) and bed porosity (Léonard et al., 2008). These parameters are necessary to develop models that can predict the behavior of the sludges during the process. Only few works can be found dealing with modeling of sludge drying (Seginer and Bux, 2006, Albino et al. 2002, Ferasse et al., 2002).

The objective of this work is to test models that can predict the behavior of the kinetics during convective drying of wastewater sludges with taking in consideration the effect of the operating conditions on the obtained results.

MATERIALS AND METHODS

Experimental set-up and procedure

The drying experiments were carried out in a discontinuous pilot scale dryer (Fig. 1) reproducing most of the operating conditions prevailing in a full scale continuous belt dryer. A fan (a) sucks ambient air that is heated up to the required temperature by a set of electrical resistances (b). Hot air flows through a bed of sludge extrudates (c) which lies on a perforated grid (d) linked to scales (e). Three operating parameters may be controlled: the temperature, the superficial velocity and the humidity of air. In this paper, we report on results obtained at increasing temperatures at constant air velocity, and room humidity. The sample was continuously weighed during the drying test and its mass was recorded every 30 s.

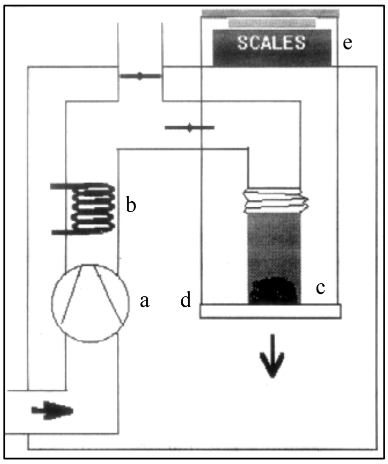

Fig. 1. Pilot scale dryer

Mathematical modeling

The obtained drying curves are fitted with the most nine commonly used models for food drying, which are: Newton or Lewis and Henderson and Pabis (Toğrul and Pehlivan, 2003 and Doymaz, 2005), Page (Karathanos and Belessiotis, 1999, Doymaz, 2005), logarithmic (Akpinar, 2006, Toğrul and Pehlivan, 2003), Two-term, Wang and Singh (Doymaz, 2005, Toğrul and Pehlivan, 2003), 3rd and 4th degree polynomial model, and finally the model of diffusion approach (Toğrul and Pehlivan, 2003). The mathematical representation of these models is shown in Table 1, where M* is the moisture ratio, representing the dimensionless moisture content of the dried product. As the equilibrium moisture content value is tending to zero, the simplified form of the moisture ratio is M/M_0.

a, b , c, d, e, k and n are parameters which vary depending on the used model.

Table 1. Mathematical models used for predicting drying kinetic curves

n°	Model equation	Name of the model
1	$M^* = \exp(-k.t)$	Newton
2	$M^* = \exp(-k.t^n)$	Page
3	$M^* = a.\exp(-k.t) + c$	Logarithmic
4	$M^* = a.\exp(-k_0.t) + b.\exp(-k_1.t)$	Two-term
5	$M^* = 1 + a.t + b.t^2$	Wang and Singh
6	$M^* = a + b.t + c.t^2 + d.t^3$	3rd degree polynomial
7	$M^* = a + b.t + c.t^2 + d.t^3 + e.t^4$	4th degree polynomial
8	$M^* = a.\exp(-k.t)$	Henderson and Pabis
9	$M^* = a.\exp(-k.t) + (1-a).\exp(-k.b.t)$	Diffusion approach

Regression analyses were done using Curve-Expert computer program. The determination of the correlation coefficient, that we note (r), was the first step and the first criterion to determine the best models. After that, the standard error noted ($\chi 2$) is determined. Of course, the model that shows the highest (r) value and the lowest ($\chi 2$) is the best fitting one.

RESULTS AND DISCUSSION

The current study is related to two types of sludges that we note (A) for the first type of sludge. It is characterized by an initial moisture content equal to 3.38 kg kg^{-1} (Dry basis). The second sludge is noted (B) and has an initial moisture of 2.63 kg kg^{-1} (Dry basis).

Previous studies have shown that sludge drying kinetics is strongly affected, with different degrees, by the operating conditions especially the temperature of the heated air and its superficial velocity (Léonard et al., 2005a). These observations are also available for food products (Bennamoun and Belhamri, 2008a, 2008b, 2006a, 2006b, Belhamri et al., 2006) and for building materials such as bricks (Bennamoun et al., 2009).

Fig. 2 and Fig. 3 show the drying curves obtained during constant operating conditions for different temperatures, for the two investigated sludges.

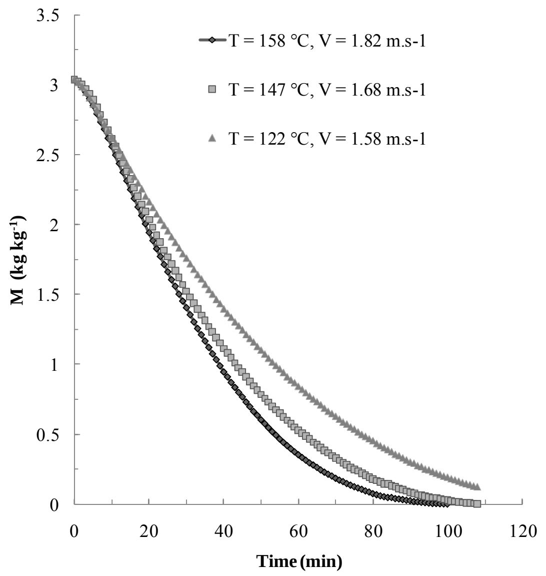

Fig. 2. Drying curve of sludge (A) for different operating temperatures

The figures show that the drying kinetics depends on the drying air temperature. Increasing the temperature of the heated air leads to the decrease of the drying time. Also, we can remark that the type of sludge affect the comportment of the drying kinetic; the moisture of the two sludges, after 50 minutes of drying, is around 1.1 kg kg-1. It can then be concluded that drying of sludge (A) is swifter than sludge (B).

The modeling results obtained with sludge (A) is represented in Table 2. Two models with best results can be selected, i.e. the Page model (n°2) and the 4th polynomial degree model (n°7). They present acceptable results for the whole studied temperatures and the correlation coefficients were between 0.9994 and 0.9996 for the first model and between 0.9998 and 1.000 for the second model. Also, the standard errors were between 0.0089 and 0.0098 for the first model and 0.0051 and 0.0029 for the second model. Similar observation can be made for sludge (B), but different values are found for the model parameters. Only parameter obtained for the two selected models are given here for sludge B. For Page model the following results have been obtained: (k) coefficient has a value of 0.0059 at temperature of 140°C and 0.0053 at 120°C and (n) coefficient is equal to 1.3307 at 140°C and 1.283 at 120°C, with a coefficient of correlation equal to 0.9997 and a standard error equal to 0.0081 at 140° and 0.9997 as value of the coefficient of correlation and 0.0064 for the standard error at 120°C. The second model present 0.9999 as correlation coefficient at 140°C and 0.9998 for 120°C with 0.0037 as standard error at 140°C and 0.0051 for 120°C. The parameters (a, b, c, d and e) have respectively the following values at 140°C: 1.0238, -0.0162, $3.1292.10^{-5}$, $6.3003.10^{-7}$, $-2.8882.10^{-9}$. These parameters have taken respectively the following values for a temperature of 120°C: 1.0336, -0.0151, $7.7294.10^{-5}$, $-1.5916.10^{-7}$, $1.0074.10^{-10}$.

The obtained results allow us to present the fitting parameters of the selected models as functions of the temperature of the heated air, which makes the model useful for multiple temperatures and for the change of the operating temperature during the drying process. The parameters of the two models are written in the Table 3 for sludge (A). The results present a correlation coefficient equal to 1 (only the correlation coefficient of (n) was equal to 0.9998). This work has not been done with sludge (B) as only temperatures were tested.

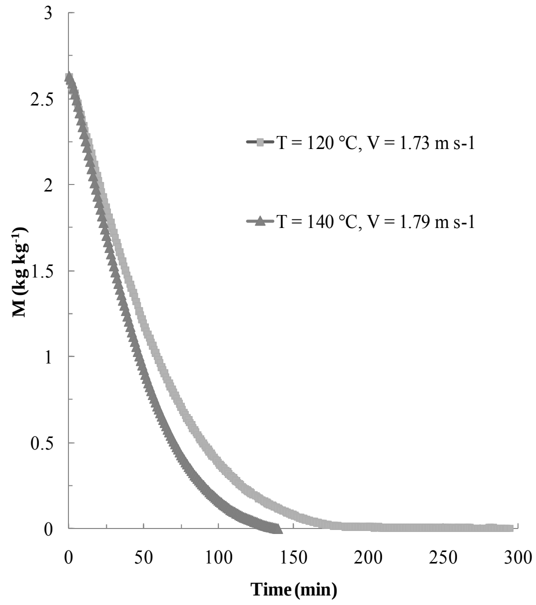

Fig. 3. Drying curve of sludge (B) for different operating temperatures

Table 3. Presentation of the different coefficients of the two selected models as function of the air temperature for sludge (A)

Model	Coefficient
Page	$k = 10^{-6} T^2 - 0.0003T + 0.0318$
	$n = 0.0050 T + 0.6660$
4th degree	$a = -5 .10^{-5} T^2 + 0.0139 T + 0.0481$
	$b = 4 .10^{-6} T^2 - 0.0012 T + 0.0672$
	$c .10^5 = -0.02 T^2 + 5.2263 T - 336.05$
	$d .10^6 = 0.0034 T^2 - 0.8638 T + 55.675$
	$e .10^8 = -0.0017 T^2 + 0.4385 T - 28.328$

The comparison between experimental and predicted values was successful for both Page model and the 4th degree polynomial model and for the two sorts of sludges, such as the results presented in Fig 4, with a coefficient of correlation near the unity.

Table 2. Temperature influence on the different studied models parameters for sludge (A)

	Temperature 158°C			Temperature 147°C			Temperature 122°C		
n°	Parameters	(r)	(χ^2)	Parameters	(r)	(χ^2)	Parameters	(r)	(χ^2)
1	k = 0.0297	0.9807	0.0620	k = 0.0265	0.9832	0.0571	k = 0.0211	0.9895	0.0418
2	k = 0.0056 n = 1.4518	0.9996	0.0089	k = 0.0058 n = 1.3998	0.9995	0.0096	k = 0.0072 n = 1.2731	0.9994	0.0098
3	a = 1.2353 k = 0.0241 c = -0.1503	0.9974	0.0230	a = 1.2290 k = 0.0215 c = -0.1494	0.9985	0.0174	a = 1.2395 k = 0.0156 c = -0.2034	0.9997	0.0073
4	a = b = 0.5711 $k_0 = k_1$ = 0.0336	0.9897	0.0462	a = b = 0.5677 $k_0 = k_1$ = 0.0299	0.9917	0.0408	a = b = 0.5439 $k_0 = k_1$ = 0.0230	0.9944	0.0309
5	a = -0.0215 b = 0.0001	0.9982	0.0189	a = -0.0192 b = $9.3077 .10^{-5}$	0.9985	0.0172	a = -0.0160 b = $6.6032 .10^{-5}$	0.9997	0.0071
6	a = 1.0497 b = -0.0237 c = 0.0001 d = $7.3171 .10^{-8}$	0.9994	0.0103	a = 1.0524 b = -0.0221 c = 0.0001 d = $1.9796 .10^{-7}$	0.9996	0.0091	a = 1.0230 b = -0.0174 c = $9.0575 .10^{-5}$ d = $-1.2468 . 10^{-7}$	0.9999	0.0036
7	a = 1.0258 b = -0.0187 c = $-8.6264 .10^{-5}$ d = $3.4758 .10^{-7}$ e = $-1.7745 .10^{-8}$	0.9998	0.0051	a = 1.0366 b = -0.0191 c = $8.5735 .10^{-6}$ d = $1.6508 .10^{-7}$ e = $-8.5593 .10^{-9}$	0.9998	0.0070	a = 1.0173 b = -0.0163 c = $4.4453 .10^{-5}$ d = $5.4165 .10^{-7}$ e = $-3.0849 .10^{-9}$	1.0000	0.0029
8	a = 1.1421 k = 0.0336	0.9897	0.0457	a = 1.1353 k = 0.0299	0.9917	0.0404	a = 1.0877 k = 0.0230	0.9944	0.0306
9	a = -3.6219 b = 0.7967 k = 0.0670	0.9989	0.0148	a = -3.5998 b = 1.2660 k = 0.0096	0.9964	0.0266	a = -1.9865 b = 1.5495 k = 0.0065	0.9991	0.0119

CONCLUSIONS

The presented results have shown that drying kinetics of wastewater sludges can be affected by temperature of the heated air, but also by the type of sludge.

Page model or the 4th degree polynomial model can be used for modeling wastewater sludges drying in a fixed bed. Simulated results are in good agreement with experimental values, with correlation coefficients near the unity and low standard errors. However, the coefficients of the selected models can change with the sludge type.

The obtained results are considered as preliminary modeling of sludge convective belt drying. This is the first necessary step to optimize in a very simple way the operating of industrial sludge dryers. As a next step, the impact of other operating conditions, i.e. air velocity and humidity, will be investigated. The range of investigated temperatures will also be extended.

NOMENCLATURE

M	moisture content	kg kg^{-1}
M*	dimensionless moisture	
t	time	min
T	temperature	°C
V	air velocity	m s^{-1}

Subscripts

0	initial value

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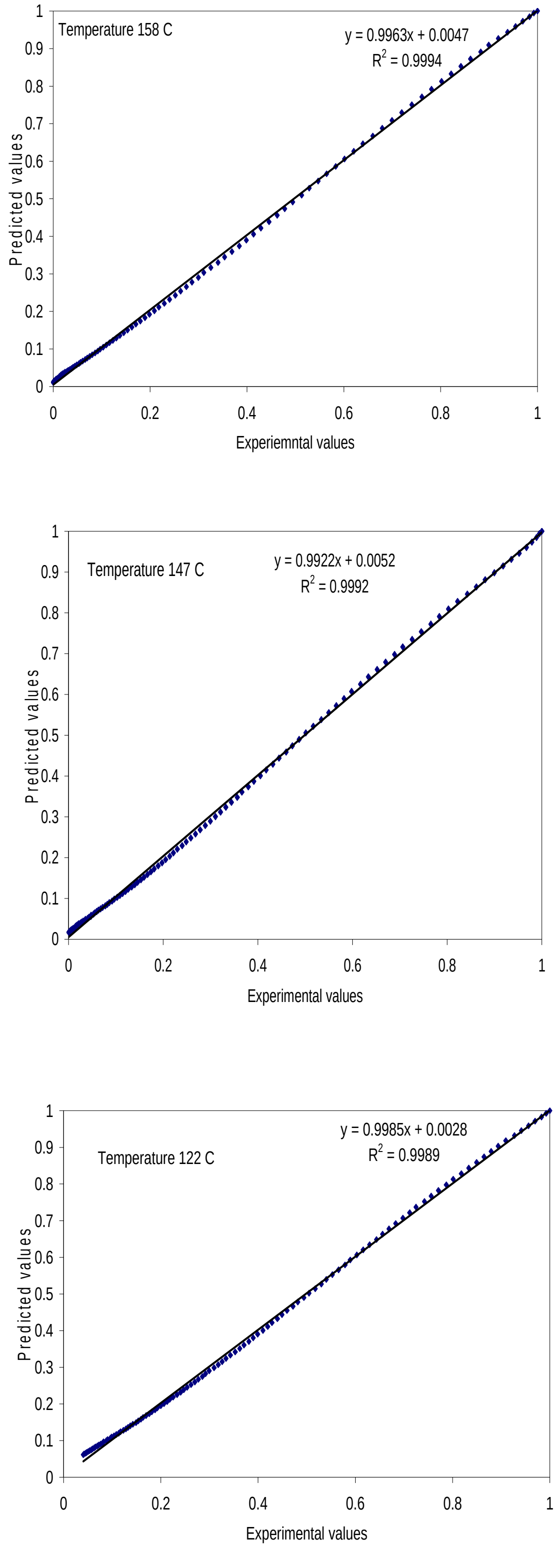

Fig. 4. Comparison between experimental and predicted values for different temperatures and using Page model applied to sludge (A)

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