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Characterisation of Residence Time Distribution in a Continuous Paddle Dryer

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ABSTRACT: A method to determine residence time distribution (RTD) of municipal sewage sludge in a continuous contact dryer with agitation has been developed. Experiments were conducted using a pulse injection of chloride sodium and by sampling and analysing the electrical conductivity of sludge leachate offline. Experiments were performed with the same operating conditions in triplicate but with a sampling interval at the wastewater treatment plant of several weeks. Accuracy and reproducibility of the method was quantified with an averaged mean residence time of 160 ± 7 min. The RTD curves shows sludge flow behavior is intermediate between a plug flow and a perfectly mixed flow. This is due to presence of paddles which induces axial dispersion on the flow.

INTRODUCTION

A drying operation is an essential and unavoidable stage to valorize sludge in incineration, pyrolysis or gasification. For instance, dry solids content from 60% to 90% are expected for co-incineration with municipal solid wastes while more than 85% are needed for pyrolysis and gasification [1]. Considering the limited separation yields of the conventional mechanical dewatering devices, those targeted dry solid contents can only be reached by partial or full drying.

Besides a uniform treatment, the flexibility of the process to adapt the final solid content of the dried sludge to the demand will be a major requirement of any sludge drying system in the near future. Presently, this flexibility does not exist. A third of the driers in operation are designed to reach a dry solid content of 65%. Whereas in the other two thirds, the dry solid content of the sludge exceeds 90%. Most often, the sludge is over dried and energy consumption of the drying system is much higher than needed. Modeling the drying process is essential to improve sustainability of sludge drying operations. Several approaches exist. The classical approach based on integral heat and mass balance equations written for input and output parameters of the process does not take into account local conditions of heat and mass transfer that may vary significantly over the apparatus. Much closer to the real process, the local approach which employs differential momentum heat and mass conservation equations requires special skills in mathematics making them inconvenient for engineers. Chemical engineers use a simpler approach which couples a hydrodynamic characterization of the reactor using the concept of Residence Time Distribution (RTD) with a kinetic model to predict average outlet concentration in a real reactor. The principle of RTD measurements [2] is to inject an inert tracer into the reactor at some initial time and to measure the tracer concentration in the outlet stream as a function of time. The RTD function which describes in a quantitative manner how much time different fluid elements have spent in the reactor is computed from the concentration-time curve. A recent literature review lists different methods and techniques which can be used for RTD determination in processes involving solids such as dryers, grinders, extruders, or mixing devices [3]. The chosen tracer should be a non-reactive species, easily detectable, and must have physical properties similar to those of the bulk product. Colored [4,5,6], chemical, and electrolyte materials [4,7] are the most common types of tracers. Drastic constraints related to safety [8] limit uses of radioactive tracers [9,10].

The present study concerns evaluation of flow pattern in a lab-scale paddle dryer (first stage of modeling methodology mentioned above) through RTD experiments. Paddle dryers are frequently used for sludge treatment but excessive drying is often noted. These dryers consist of a horizontal heated trough containing at least two rotating heated shafts with wedge-shaped

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paddles welded on each shaft. The only function of these paddles is to ensure a good mixing in the radial direction to homogenize product temperature and to avoid clogging. Since these paddles do not contribute to product transport, a plug flow is expected to occur. To date we only identified one study characterizing the RTD in a sludge paddle dryer [11]. Nickel chloride ($NiCl_2$) and manganese chloride ($MnCl_2$) were used as tracers. Dried sludge samples were pretreated using dry ash and wet digestion methods before amounts of nickel and manganese are determined by flame atomic absorption spectrometry. Results emphasize that the flow pattern in a large-scale paddle dryer equipped with four rotating shafts is not a simple plug flow. Back mixing of the sludge occurs, especially near the middle of the dryer where the sludge consistency is sticky. However, the RTD analysis was subjected to large inaccuracies as the concentration-time curve was incomplete. Indeed, even if the RTD experiment lasted six hours, no experimental data were collected to describe the tail of the concentration-time curve. Consequently, the area under the concentration-time curve and residence time were under-estimated. In addition, reproducibility and accuracy of the method are not discussed. The proposed analytical protocol is time-consuming. Therefore, a simpler method based on a pulse injection of sodium chloride into the dryer and detection by conductimetry is proposed in the present paper. The analytical protocol and lab-scale dryer used for the experiments are described in section 2. Special attention is paid to the calibration curve in particular. Reproducibility and accuracy of the method are discussed in section 3.

Table 1. Initial Dry Solid Contents.

Experiment 1	Experiment 2	Experiment 3
19.1 ± 0.1%	19.3 ± 0.1%	21.6 ± 0.1%

MATERIAL AND METHODS

Feed Material

Sewage sludge was sampled in the urban wastewater treatment plant (WWTP) of Albi city (France). The WWTP, designed for a capacity of 91,000 population equivalent (PE) but operating at 60,000 PE, implements a conventional extended aeration process, a nitrification/denitrification process, a biological phosphorus removal, and an anaerobic digestion process. Three drying experiments were performed requiring sampling of three different sludge batches. Sludge was sampled after centrifugation and stored at 4°C in a tight container. Experiments were performed within 1 week after sampling.

Continuous Contact Dryer

Currently, drying and RTD experiments are performed on a lab-scale (15 kg/h) continuous agitated contact dryer designed and built by the authors [See Figure 1(a)]. This dryer consists of a U-shaped jacketed trough with a rotating shaft. The trough is 1m long, 0.32 m high, and has an inner diameter of 0.16 m. Three U-shaped electrical resistances (Chromalox, Soissons, France) 0.33 m long each are inserted in the double wall. Each can supply up to 6.10^4 W/m^2. Three

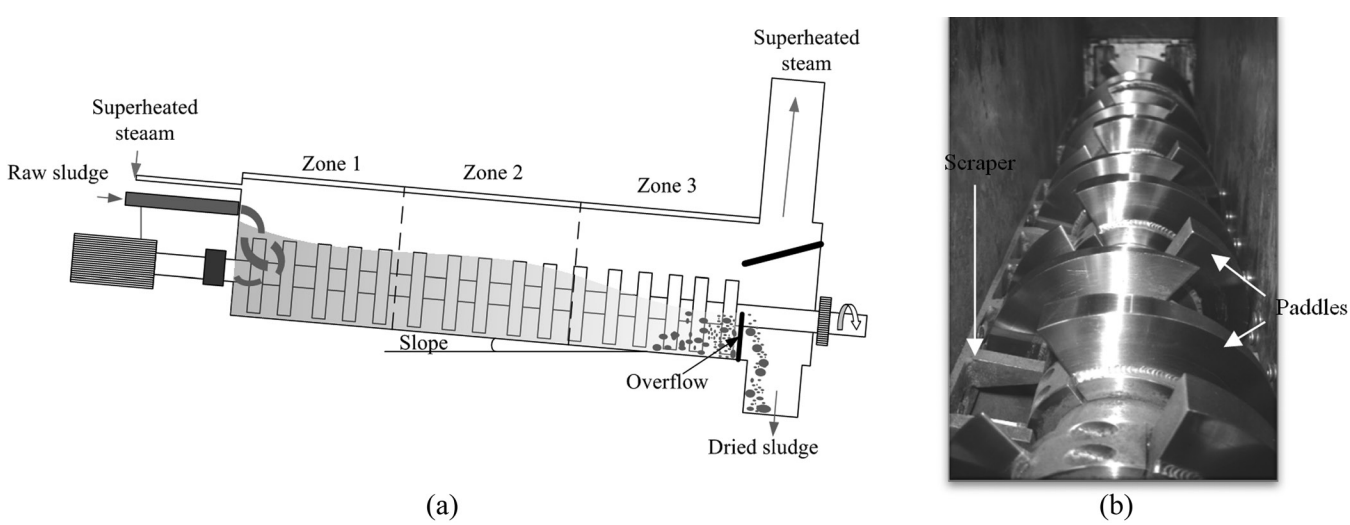


Figure 1. *(a) Schematic of the laboratory indirect dryer and (b) photo of the mixing device.*

temperature sensors, one for each electrical resistance, are used for thermal regulation of the dryer wall. These sensors set at 0.001 m from the wall front side in contact with the sludge are positioned at 0.16, 0.50, and 0.83 m from the dryer inlet, respectively. To limit thermal losses towards the outside, the trough is insulated with a 5 cm thick Superwool® HT Fibers (Eurotech, Cessales, France).

This trough is closed by a removable and tight hood with three trap doors. For each zone of 0.33 m length, four heating cartridges (Chromalox, Soissons, France) are inserted in the 6 cm diameter hollow shaft. Each can supply up to 10^5 W/m^2. Three temperature sensors, one for each zone, are used for thermal regulation of the rotor. These sensors set at 0.015 m from the outward are positioned at 0.12, 0.46, and 0.79 m from the dryer inlet. Eighteen full wedge-shaped paddles are screwed onto the rotor and heated by conduction. In the current configuration, paddles are regularly distributed along the shaft. Scrapers formed to interact with paddles are positioned on the trough [See Figure 1(b)]. A 4 kW asynchronous motor with a variable frequency drive (Leroy Somer, Colomiers, France) permits a precise adjustment of the rotor's speed between 10 and 60 rpm. A contactless DR2112 torque meter (LR Mesures, Libourne, France) for measurements up to 500 Nm max equips the stirrer. The drier rests on a support which can be tilted ± 5°. A Moineau 2.6 IVA pump (PCM, Levallois Perret, France) conveys mechanically dewatered sludge from the feed hopper of a capacity of 40 l to the dryer. Pump speed is controlled with a frequency inverter. Sludge is fed into one end of the trough and flows due to gravity into the dryer slope and mechanical agitation at the opposite end where dry material is discharged. Solids hold-up in the dryer is controlled through an adjustable overflow. Superheated steam (1 atm, 160°C) produced by a 4 kW steam generator and a 0.3 kW superheater (TATT, Eybens, France) is used as sweeping gas. The sweeping gas and vapors exhausted during processing are carried out through a central exhaust port.

Operating conditions were selected and set for drying experiments. They are summarized and may be seen in Table 2.

Table 2. Operating Conditions.

Wet basis mass flow rate		4.7 kg/h
Dryer slope		2°
Dryer wall temperature		160°C
Stirrer speed		7 rpm
	Temperature	160°C
Superheated steam	Mass flow rate	1.1 kg/h
	Pressure	1 atm

Tracer

Choice and Test Validation

Choice of tracer was made considering tracers currently used in wastewater treatment studies, measurement techniques available in the lab, repeatability and accuracy of the measurement techniques in regard to the required degree of precision, and "thermal stability" with the drying conditions [12]. In the field, three tracers are mainly used: lithium chloride LiCl [13,14,15], sodium chloride NaCl [16], and rhodamine [17,18,19,20]. Sodium chloride is a popular choice for tracer test studies given its low cost and ease of monitoring. Electrical conductivity was retained as the detection method and NaCl was selected as the tracer.

Influence of the tracer powder dispersion method on sludge structure and viscosity, drying kinetics, and sticky phase were investigated. Even if mixing in a planetary mixer changes rheological properties of raw sludge and increases its stickiness, it does not have any influence on the drying kinetic and sticky phase [21].

Concentration Determination with Calibration Curve

To implement the detection method, sludge samples must be dried at 105°C for 24 h and leached during 24 h with demineralised water (m_{water}/m_{DM} = 10, where m_{water} and m_{DM} are water and dried matter masses, respectively).

A series of standards in demineralised water and sludge samples across a range of concentration close to

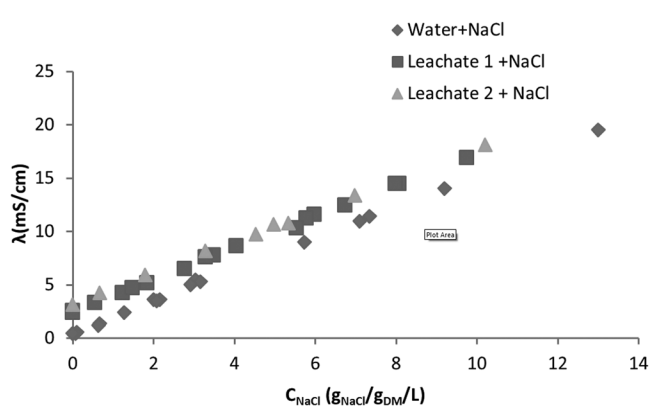


Figure 2. *Calibration curves.*

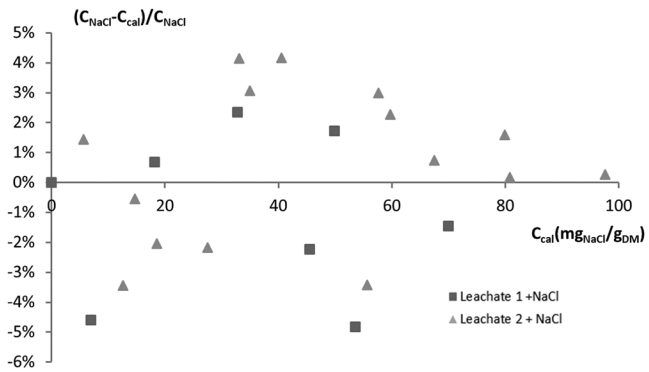


Figure 3. *Accuracy of the calibration curve.*

the expected concentration of NaCl in the leachate has been prepared. Concentration of NaCl was measured with a DCM210 conductivity meter (MeterLab, Copenhagen, Denmark). Calibration curves for NaCl in water and NaCl in sludge leachates are plotted in Figure 2. To investigate influence of sludge composition, two batches were sampled at an interval of one month at the WWTP (leachate 1 and leachate 2).

As expected, electrical conductivity (λ) for standards prepared in demineralised water and sludge leachates varies linearly with NaCl concentrations. Data were fitted according to Equation (1). The slope parameter, *a*, and the conductivity of the background (demineralised water and sludge), λ_{ini}, are displayed in Table 3.

$$\lambda = \lambda_{ini} + a * C_{NaCl} \quad (1)$$

Translation of the curves induced by conductivity of the background has to be considered for each sludge batch. Indeed, a change of initial sludge conductivity will induce an over- or under- estimation of tracer concentration.

Table 3. Coefficients of Equation (1).

	Water + NaCl	Leachate 1 + NaCl	Leachate 2 + NaCl
λ_{ini} (mS.cm^{-1})	0.44	3.18	2.46
a (mS.gDM.L.cm^{-1}.gNaCl^{-1})	1.48	1.47	1.49
r^2	0.991	0.98	0.990

The calibration equation that should be used to calculate NaCl concentration for unknown samples Ccal is given by Equation (2).

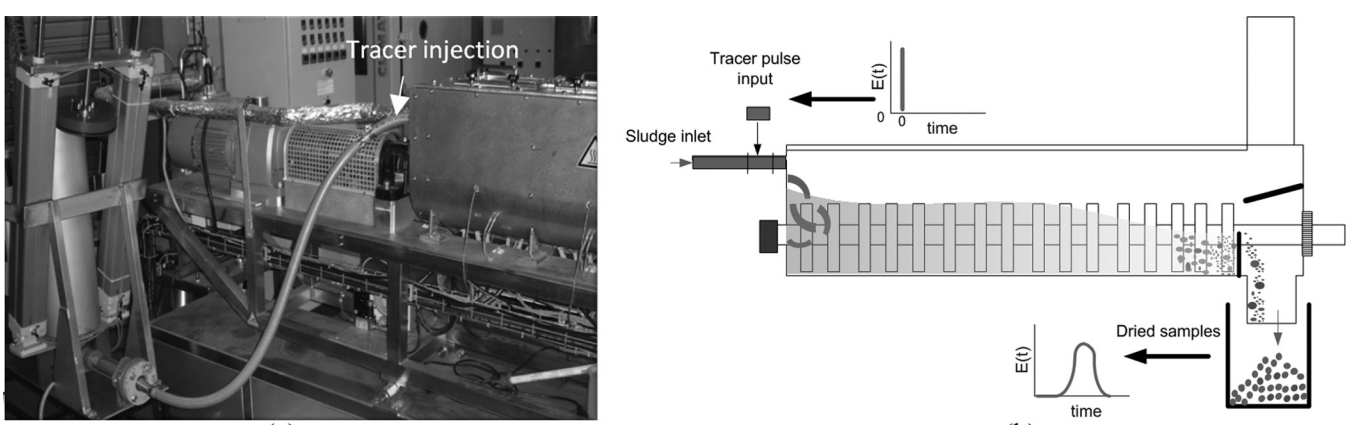
$$C_{cal} = \frac{\lambda - \lambda_{ini}}{1.48} \quad (2)$$

Figure 3 shows the relative error in the calculation of the concentration by using the calibration equation. Residual errors are randomly distributed for two leachates and maximal residual error on the prediction is at 5%.

Tracer Injection and Sludge Sampling

An amount of 90 g of NaCl powder, determined in order to have a minimum pic of conductivity three times higher than the background conductivity, was mixed with raw pasty sludge. Preparation was then injected at the inlet of the dryer [See Figure 4(a)] in a short time to obtain a Dirac function.

The whole sludge outflow mass was sampled and analysed [See Figure 4(b)]. After introduction of the tracer, samples were taken every 5 or 10 min during a minimum of 6 hrs, then dried, and then leached as described before.



(a) (b)

Figure 4. *(a) Tracer injection and (b) sampling method.*

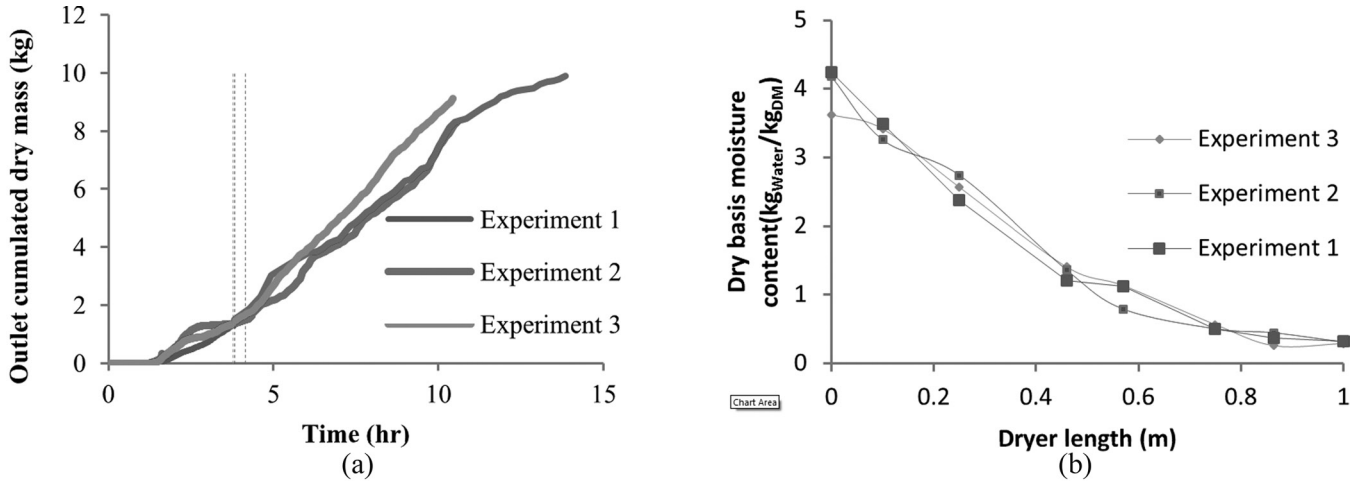


Figure 5. *(a) Outlet cumulated dry mass and (b) dry basis moisture content distribution along the dryer (kg_{Water}/kg_{DM}).*

Data Analysis

Knowing the NaCl concentration, the exit age distribution function $E(t)$ was calculated according to Equation (3):

$$E(t) = \frac{C_{NaCl}(t)}{\int_0^\infty C_{NaCl}(t)dt} \tag{3}$$

The mean residence time, t_s, the variance of the residence time, σ^2, and the dimensionless variance, σ_D^2, are given in Equations (4)–(6):

$$t_s = \int_0^\infty t.E(t)dt \tag{4}$$

$$\sigma^2 = \int_0^\infty (t - t_s)^2 E(t)dt \tag{5}$$

$$\sigma_D^2 = \left(\frac{\sigma}{t_s}\right)^2 \tag{6}$$

The averaged dryer velocity, v_{mean}, is then given by Equation (7):

$$v_{mean} = \frac{L}{t_s} \tag{7}$$

where L is the length of the dryer.

RESULTS AND DISCUSSION

Drying Experiments

Three drying experiments were performed with operating conditions displayed in Table 2. In particular, the wet basis mass flowrate at the inlet is kept constant for the three experiments. Cumulated mass of dry solids recovered at the dryer outlet during each experiment is plotted in Figure 5(a). As dry solid content of the raw sludge is higher for experiment 3, the slope of the corresponding curve on Figure 5(a) is slightly larger.

As seen in Figure 5(b), the dry basis moisture content distribution along the dryer is reproducible for the three experiments. Drying drastically reduces dry moisture content from 4 kg_{Water}/kg_{DM} at the entry of the dryer to 0.39 kg_{Water}/kg_{DM} at the outlet.

Drying rate of indirect dryers usually ranges between 5 and 20 $kg/m^2/h$ [1,22]. Average drying rate for the three experiments is lower than 5. Drying rate has been calculated here taking the whole heated wall surface into account (1 m^2) like for industrial paddles dryers. However, the filling rate of the dryer is low and the heating surface (wall and stirrer) is partially covered by the sludge (See Figure 6). As a result the effective drying rate is under estimated.

The sludge looks like a viscous fluid from the dryer entry to 0.33 m in the first zone [See Figure 6(a)]. Averaged drying rate for the three experiments is 5.22 $kg/m^2/h$ and a decrease of dry basis moisture content from 4 to 2 kg_{water}/kg_{DM} is observed. In the

Table 4. Characteristics of the RTD.

	Experiment 1	Experiment 2	Experiment 3
t_s (min)	156	169	157
σ_D^2	0.36	0.17	0.17
v_{mean} ($m.h^{-1}$)	0.29	0.27	0.27
t_{app}/t_s	0.28	0.27	0.30

(a) (b) (c)

Figure 6. *Photo of the sludge in zone 1 (a), zone 2 (b), and zone 3 (c).*

second zone [See Figure 6(b)], from 0.33 m to 0.66 m, a change of the sludge consistency from pasty at 2 kg_{water}/kg_{DM} to sticky at 0.75 kg_{water}/kg_{DM} may be observed. This change induces a decrease in the drying rate to 3.61 $kg/m^2/h$. Volume of the sludge considerably decreases and the heated surface is less covered than in zone 1 [See Figure 6(b)]. In the third zone of the dryer, from 0.66 m to 1 m, the material is granular and average drying rate strongly decreases to 0.97 $kg/m^2/h$ as the dry basis moisture content is reduced from 0.75 to 0.39 kg_{water}/kg_{DM}. Withdrawal resulting from water evaporation further reduces contact surface.

RTD Experiments

Figure 7 shows conductivity and percentage of recovered tracer versus sampling time after the tracer injection. As background conductivity was higher for experiment 1, the corresponding curve is shifted upwards. Nevertheless, the shapes of the three curves are similar.

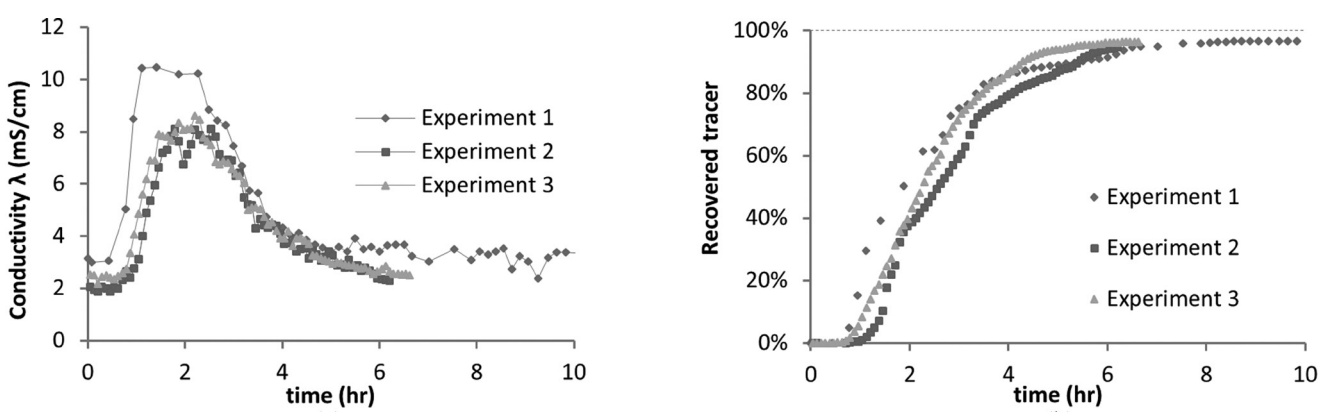
Approximately 6 hr after tracer injection, electrical conductivity of the leachates tends towards its initial value. Percentage of tracer recovered reaches at least 95%. Values for mean residence time and averaged velocity in the dryer are listed in Table 4 for each of the drying experiments. For an averaged mean residence time of 160 min, the standard deviation obtained is 7 min which represents 4.5% change and thus establishing acceptable reproducibility of results.

Figure 8 shows the normalized, $E(\theta)$, and cumulative, $F(\theta)$, exit age distribution plotted against normalized time θ defined as the ratio t/t_s.

Cumulative exit age distributions of a perfect plug flow (PFR) and perfectly mixed flow (CSTR) reactor are also added on Figure 8(b). RTD distribution of the sludge in the paddle dryer lies between these two ideal cases.

Onset time, t_{app}, is introduced corresponding to time at which the beginning of the peak is detected. The ratio t_{app}/t_s can provide information about flow. It is equal to 1 for a plug flow and to 0 for a perfectly mixed reactor. This ratio reaches 0.28 here. Flow behavior is closer to a perfectly mixed flow than a plug flow as a result.

Figure 9 shows cumulative RTD curves for different solids unit operations together with the one achieved for experiment 2. In rotary drums and milling processes, the product flow is theoretically only due to gravity. The flow in a rotary drum process is known to tend toward a plug flow (curve a). The axial dispersion is low



(a) (b)

Figure 7. *(a) Conductivity measurements and (b) percentage of recovered tracer versus sampling time.*

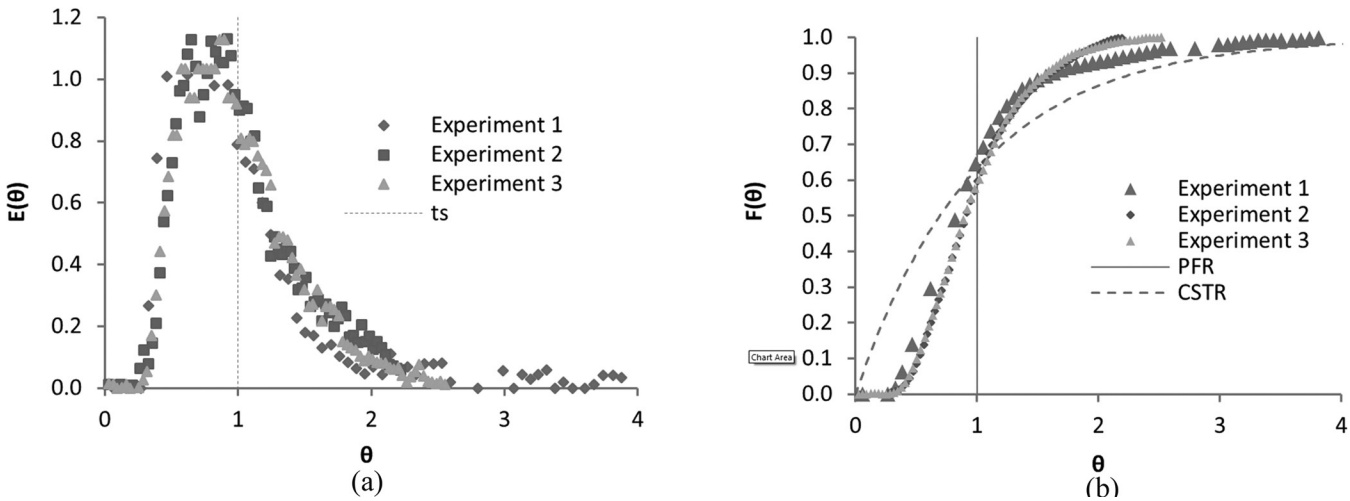


Figure 8. *(a) Normalized exit age distribution and (b) normalized cumulative exit age distribution.*

and all particles have practically the same residence time [23]. On the contrary, flow in the majority of the milling processes is considered as fully mixed flow (curve b) with high dispersion induced by milling balls and particles having different residence times [24].

In an extruder made up of a screw conveyer and a continuous screw blender the product flow is due to the rotation of the screw. The screw is designed only to displace the solid and a flow close to plug flow is chosen for solids conveying [See Figure 9(c)] [25]. On the contrary, high mixing is searched in a continuous blender and the screw is designed to obtain a flow close to a perfectly mixed flow [curve (d)] [5]. Different flows in extrusion may be obtained [curves (e) and (f)]. For example, Zuilichem *et al.* (1999) demonstrated the impact of different screw geometries on RTD distribution of food materials [26]. Axial mixing is improved by using paddles but there is a lack of conveying. Lead element provides reasonable conveying but axial mixing is very poor. Paddles induce dispersion of the RTD which tends toward a perfectly mixed flow. A combination of paddles and lead elements seems to be the solution to achieve strong and homogeneous treatment in the system.

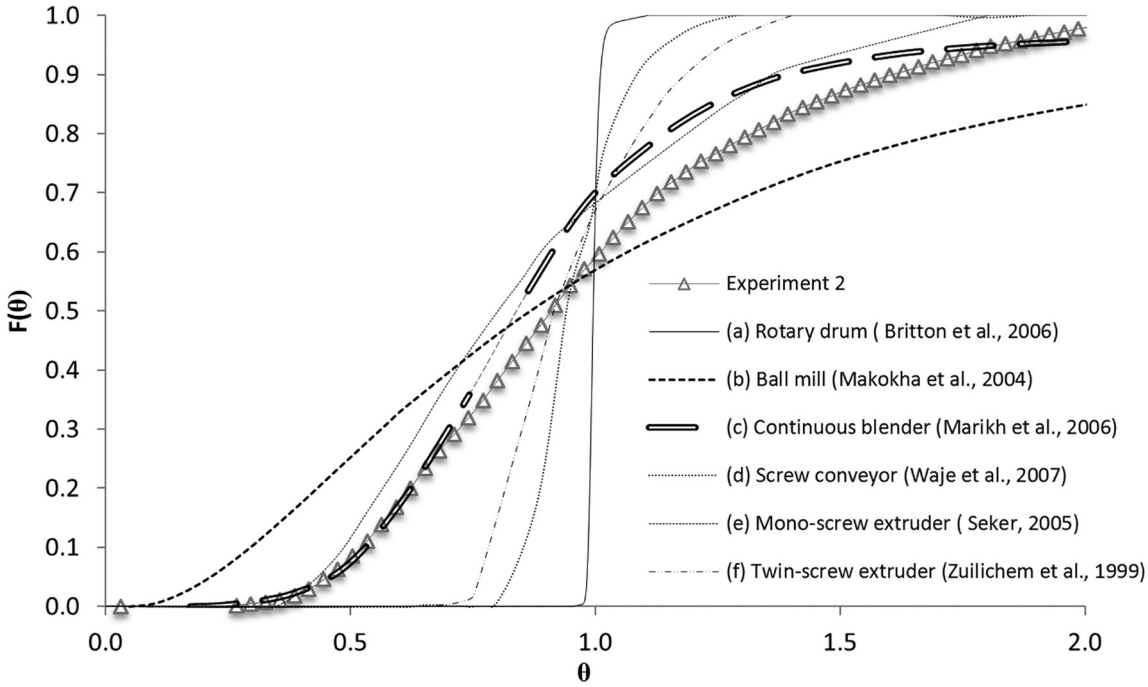


Figure 9. *Normalized cumulative curves F(θ) for experiment 2 and for different solid technologies found in the literature: (a) rotary drum, (b) ball mill, (c) screw conveyor, (d) continuous blender, (e) single-screw extruder, and (f) twin-screw extruder.*

CONCLUSION

A method used to characterize residence time distribution (RTD) of sewage sludge in a contact dryer with agitation has been developed. Injection and detection of a NaCl tracer in the leachate is a simple and accurate method for determination of RTD curves. A calibration curve is required to implement this method and conductivity of the raw sludge must be characterized for each experiment.

Reproducibility of drying and RTD experiments has been characterized for three sludge batches. The dry basis moisture content distribution along the dryer was reproducible and normalized exit age distributions are superimposed for the three experiments. A standard deviation of 4.5% for an average mean residence time distribution of 160 min was noted.

It appears that sludge flow behavior is intermediate between a plug flow and a perfectly mixed flow. Although part of the flow is due to gravity, presence of paddles induces axial dispersion.

Response surface methodology will be used to study influence of the main processing parameters such as stirring speed, angle of inclination, and mass flow rate in future works. Use of a model based on the theory of Markov is actually under development. Flows of sludge and vapor in the dryer are represented by two parallel chains which can exchange heat and/or mass. Each chain contains a finite number n of perfectly mixed cells. The transport of the medium along a chain is described by the matrix of transition probabilities. Transition probabilities between cells of the product chains are governed by a single parameter known as parameter of internal recirculation, R. The study should show if the evolution of this parameter in the model can be linked to drying kinetics and viscosity evolution in the dryer.

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