Convective Drying of Mixtures of Sewage Sludge and Sawdust in a Fixed Bed

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*ABSTRACT. This work is part of a project aiming at developing a renewable fuel for gasification purposes, through the convective drying of sludge/wood mixtures. The first step consists in characterizing the drying behaviour of sludge/sawdust mixtures, in a convective fixed bed dryer. In particular, the influence of the mixing step (no mixing against 30 s at 40 rpm) and the sawdust/sludge ratio (1/9, 2/8, 3/7 and 4/6 on a dry basis) have been investigated, as well as the drying temperature (50 °C, 80 °C and 110 °C). As showed in a previous work, the addition of dry matter into sludge has an impact on the initial 3D structure of the bed of extrudates to be dried. Moreover, it is well known that the volume shrinkage occurring during sludge drying will affect the drying velocity. In this study, X-ray tomography, a non-invasive imaging technique, is used to assess changes in volume, porosity and exchange surface between the beginning and the end of the drying process. Results first confirm the importance of the mixing step on the drying behaviour: the drying rate of the mixed sludge is slower than the one of original sludge. Nevertheless the addition of sawdust is shown to have a positive impact on the drying process from mass ratio of 2/8, with observed drying rates higher than for the original sludge. During the whole drying process, the volume and exchange surface of the sample increase and the porosity decreases as the mass ratio increases. These results indicate that the air and the sample contact more fully with more sawdust addition, resulting from bed expansion and exchange surface increase. Hence, the* *heat and mass transfer efficiency between the air and the material increases and consequently the drying rate. Further work will be done in order to assess the impact of the drying temperature and to characterize the behaviour of these samples during pyrolysis using thermo gravimetric analysis.*

*KEYWORDS:* *Sewage sludge, Sawdust, Convective drying, Mixing, Shrinkage, X-ray tomography*

# Introduction

Because of the high amounts of sludge produced within wastewater treatment plants (WWTPs) worldwide for several years and the increasingly stringent environmental regulations (Vesilind and Spinosa 2001, Spinosa 2001), the treatment of sludge has become one critical issue. In the past years, lots of technologies have been used for sludge treatment, such as land application, composting, landfilling, and incineration, but it was found that sludge moisture content was a critical parameter governing the feasibility of various final disposal routes (Lee and Liu 2004). It is now well established that thermal drying operation, after mechanical dewatering, is an essential step prior to current sludge treatment valorization options. Nevertheless there are still some attempts to find new valorization routes for sludges. In this work, it is proposed to generate an original renewable fuel that could enter a gasification process, by drying mixture of sludge with sawdust. Sawdust/sludge mixtures are extruded and dried in fixed bed convective dryer. Sawdust addition can be seen as a way of reinforcing the texture of very soft and pasty sludge which are very difficult to be dried. Positive effects are expected, similarly as the one obtained when performing back mixing of dried sludge: expansion of the sludge bed and enhancement of the area available for heat and mass transfer (Léonard *et al*. 2008). Besides the improvement of the drying kinetics, sawdust also brings organic matter useful for gasification. This material is produced in large amount by the forest industry and also needs safe disposal solutions (Berghel and Renstrom 2002). In this context, the present work aims to determine the effect of sawdust addition operation on the convective drying kinetics of wastewater sludge. X-ray tomography, a non-destructive imaging technique, is used to follow the 3D characteristics of the bed during drying (shrinkage, exchange surface, porosity, ..).

# Materials and Methods

## Materials

Sludge was collected after the mechanical dewatering step in one classical WWTP (Grosses Battes, Belgium). The moisture content was determined according to standard methods (ASAE 1996) and the value was 85.5% (wet basis).

 Oak sawdust was collected from a wood factory (‘Industrie du bois’, Vielsalm, Belgium) and the moisture content (wet basis) was 30%.

 In this paper, the drying behaviour of several samples was tested: the original sludge, the original sludge after mixing and some mixtures of sawdust with sludge. A kitchen machine (KM1000, PROline) with a beater was used to prepare the samples. The mass ratio (expressed on a dry matter basis) of sawdust/sludge were 1/9, 2/8, 3/7 and 4/6. Sludge and sawdust were mixed during 30 s at 40 rpm. The same protocol was used to mix the original sludge without any sawdust addition. The samples were then extruded through a circular die of 12 mm before drying, forming a bed of extrudates on the dryer perforated grid. The weight of the bed of extrudates was fixed at 500 g in all the experiments.

## Methods

**Pilot-scale dryer**

The drying experiments were carried out in a discontinuous pilot-scale dryer, as shown in a previous paper (Léonard *et al*. 2008). In this study, three temperatures were used: 50 °C, 80 °C and 110 °C, with air velocity fixed at 2 m/s. No additional air humidification was carried out. During the whole study, the ambient air humidity was close to 0.007 kgwater/kgdry air. The sample was continuously weighed during the drying test and its mass was recorded every 30 s.

**X-ray tomography**

X-ray tomography was used to determine the influence of sawdust addition on the initial and final structures of the beds of extrudates. This non-invasive technique, originally developed for medical applications, allows obtaining 2D cross sections and 3D images of the bed. The X-ray tomography used in this paper was a high-energy X-ray tomograph, developed by Toye *et al*. (2005). The energy of the source is 420 kV, the pixel size of the image is 0.359 mm and the distance between two slices is 2.2 mm.

 The volume, bed porosity and total exchange surface available for heat and mass transfer were determined by image analysis of tomographic images (Léonard *et al*. 2008).

# Results and discussion

## Drying Behaviour

The influence of the mixing step (no mixing against 30 s at 40 rpm) and of the sawdust/sludge ratio (1/9, 2/8, 3/7 and 4/6 on a dry basis) has been investigated, as well as the drying temperature (50 °C, 80 °C and 110 °C). Fig. 1 shows the drying rate vs. water content. As can be seen, the regular patterns of the drying rate curves are almost the same at different drying temperatures. But it is clear that higher drying rates are obtained at increasing temperatures.

Fig. 1. Drying rate vs. water content.

 Results first confirm the importance of the mixing step on the drying behaviour (Huron *et al*. 2010): the drying rate of the sludge having been mixed is slower than the one of the original sludge (Fig. 1), during most of the drying process. Nevertheless the sawdust addition is shown to have a positive impact on the drying process from mass ratio of 2/8, with observed drying rates on Fig. 1 higher than for the original sludge. The positive effect of sawdust addition is clearly observed: for different drying temperatures, the drying rate globally increases with increasing addition of sawdust, while the initial water content decreases as well as the total amount water to be removed. Indeed the same mass is introduced for each experiment.

## Volume and shrinkage

In this study, X-ray tomography, a non-invasive imaging technique, is used to assess changes in volume, porosity and exchange surface between the beginning and the end of the drying process.

 The apparent volumes occupied by the bed of samples before and after drying at different drying temperatures are shown in Fig. 2. As can be seen, the regular patterns of volumes are almost the same at different drying temperatures too. When performing a mixing step before drying, the volume decreases a little. Then the initial volume before drying slightly increases with increasing addition of sawdust. However, the final volume obtained after dying increased in more marked manner with increasing addition of sawdust.

Fig. 2. Volume of sample bed before and after drying vs. mass ratio.

 Fig. 3 shows the volume shrinkages of samples after drying at different drying temperatures. As can be seen, the volume shrinkage becomes smaller with increasing addition of sawdust. This means that the sawdust braces the structure of sample during drying. By comparing the results at different drying temperatures, the volume shrinkage obtained for the same mass ratio of sawdust/sludge is smaller when the drying temperature is higher. This can be easily explained by a “crust formation’ phenomena (Schultz and Schlünder 1990, Gac and Gradoń 2013).

Fig. 3. Volume shrinkage after drying vs. mass ratio.

## Bed porosity and total exchange surface

In the sawdust addition experiments, the variations of the bed porosities and total exchange surfaces before and after drying were also investigated. The influence of sawdust addition on the structure of the bed was quantified by image analysis of the cross sections obtained by the X-ray tomography. Fig. 4 and Fig. 5 show the bed porosity and the total exchange surface vs. mass ratio respectively. For the three different drying temperatures, the regular patterns are almost the same.

 Before drying, the change of the bed porosity is not obvious when comparing without and with mixing. But the decrease of the total exchange surface is obvious after the sludge is mixed. Afterwards, the bed porosity decreases and the total exchange surface increases with the increasing addition of sawdust.

 After drying, the total exchange surface of the sample increases and the bed porosity decreases with the increasing addition of sawdust.

Fig. 4. Bed porosity vs. mass ratio.

Fig. 5. Total exchange surface vs. mass ratio.

## Discussion

Apparently, the sawdust addition changes the structure and property of the bed of sample submitted to drying. Because the sludge and the sawdust are two different materials, they need to be mixed and homogenized before extrusion. In previous works, it was found that back mixing and liming changed the rheological property of sludge (Léonard *et al*. 2008, Léonard *et al*. 2009), in relation with the structure of the bed. In particular, the cohesion of the sludge decreased with longer mixing time and higher mixing velocity. Consequently, the rigidity of sludge extrudates decreased, producing fixed beds of product developing lower exchange areas, and leading to the decrease of the drying rate. So in this work, a low mixing rate (40 rpm) and a short mixing time (30 s) were chosen for the experiments.

 In accordance with the convective drying theory, three periods can be identified (Deng *et al*. 2011, Bennamoun *et al*. 2013).

 The preheating period exists which represents a period of adaptation of the sample to the drying conditions. During this period, the drying rate increased considerably.

The next period observed is the constant rate period. It is obvious that this period is very short in the experiments. During this constant rate period the evaporation takes place at the surface of the wet solid and the solid assumes a constant equilibrium temperature, just as a free liquid surface is maintained at the wet-bulb temperature of the air (Sherwood 1929). As explained by Deng et al. (Deng *et al*. 2011), the evaporated water in this period is free water. In most published papers, the surface change related to shrinkage is not taken in consideration in this period. To be correct, the discussion should be made on the existence of a constant drying flux period. Not taking these physical changes into consideration can lead to the absence of a constant drying flux period in the graphical representation (Deng *et al*. 2011). As can be seen, the drying rate in this period increases with the increasing addition of sawdust. This observation can be linked with changes in the total exchange surface developed by the samples. Fig. 6 shows the maximum drying flux obtained during our experiments when divided the maximum drying rate by the initial value of the total exchange surface, obtained through X-ray tomography. It is obvious that the drying flux is dependent on the drying temperature. Higher drying temperature leads to higher drying flux. As can be seen, there is only a modest variation in the maximum drying flux with the increasing addition of sawdust. This is in agreement with externally controlled heat and mass transfers, as drying operating conditions were identical. Indeed, during the constant flux period occurring just after the preheating zone, the drying flux is independent of the sludge nature but only depends on air temperature, velocity and humidity (Léonard *et al*. 2008). This also confirms that the positive effect of sawdust lies on the expansion of the sludge bed, at least at the beginning of the drying process.

Fig. 6. Maximum drying flux vs. mass ratio

 The third period observed is a long falling rate phase. In this period, the drying rate decreases with decreasing moisture contents. For the original sludge, only one falling rate zone exists and the second falling rate zone is not obvious, as observed by other researchers (Tao *et al*. 2005a, Tao *et al*. 2005b). However, a second falling rate zone appears after the mixing step. As can be seen in Fig. 1, the decreasing drying rate zone of the mixed sludge can be obviously divided into two distinct zones. It is also found that the second falling rate zone becomes weaker with the increasing addition of sawdust.

The first decreasing zone is characterized by a linear relation between the drying rate and the water content. In this zone, the evaporation still happens at the solid surface, so the internal diffusion of liquid is not controlling and the decrease in drying rate is in fact related to the shrinkage of the bed and the decrease of the exchange surface. It is found that the drying rate decreases linearly as the total exchange surface decreases for the original sludge during the whole drying, as can be seen in Fig. 7. Moreover, the relationship between the volume shrinkage and drying time was investigated, as shown in Fig. 8. For the original sludge, the volume shrinks very fast during the first 22 min. Then the volume shrinks at a slower rate and after 90 min the volume remains constant.

The second decreasing zone is characterized by a curve protruding upwards when the drying rate is plotted vs. the water content. In this zone, the drying is taking place with internal liquid diffusion controlling and there is a tendency for the actual evaporation to occur within the solid structure rather than at the surface (Sherwood 1929). From Fig. 7 it is evident that the curve of the sample of mass ratio of 2/8 can be divided into two regions. In the first region the relation between the drying rate and exchange surface (or water content) is linear. Then in the second region the slope becomes larger. The drying rate decreases faster with the same total exchange surface reduction comparing to the first region. This means the internal liquid diffusion becomes more important in this second region and parts of evaporation happen inside the sample.

Fig. 8 compares the volume shrinkages of the two samples. It shows shrinkage is almost the same until 45 min of drying. But after 60 min, the volume of the sample of mass ratio of 2/8 remains constant while the one of the original sludge continues to decrease. It is earlier than the original sludge. Moreover, the volume shrinkage of the sample of mass ratio of 2/8 after drying is smaller than the original sludge. This means that the sawdust reinforces the texture of sludge and enhances the heat and mass transfer. As mentioned above, the second decreasing zone is the most obvious for the mixed sludge and become weaker with the increasing addition of sawdust. This means the mixing step changes the internal structure of sludge and increase the resistance of internal liquid diffusion. Beyond that, the sawdust addition decreases the resistance of internal liquid diffusion. One hypothesis could be that sawdust modifies internal porosity and tortuosity of the samples, affecting mass transport.

Fig. 7. Drying rate vs. total exchange surface during drying (Temperature=80 °C, velocity=2 m/s)

 Fig. 8. Volume shrinkage vs. drying time (Temperature=80 °C, velocity=2 m/s)

# Conclusions

This work investigated the influence of sawdust addition on the sewage sludge drying. The influence of the mixing step (no mixing against 30 s at 40 rpm) and the sawdust/sludge ratio (1/9, 2/8, 3/7 and 4/6 on a dry basis) have been investigated, as well as the drying temperature (50°C, 80°C and 110°C). The drying experiments were carried out in a pilot-scale dryer. X-ray tomography was used to determine the volume, bed porosity and total exchange surface. The mixing step has a negative impact on the drying process and the drying rate of the mixing sludge is slower than the original sludge. The mixing step changes the internal structure of sludge and increase the resistance of internal liquid diffusion and then the second falling rate zone appears. Nevertheless the sawdust addition is shown to have a positive impact on the drying process from mass ratio of 2/8, with observed drying rates higher than for the original sludge. The permeability increases and the resistance of internal liquid diffusion decreases with sawdust addition and then the second falling rate zone becomes weaker. Moreover, the volume and total exchange surface of the sample before and after drying increase with sawdust addition. By comparing the original sludge and the sample of mass ratio of 2/8 it is found that the volume shrinkages are almost the same in 45 min and then the volume shrinkage of the sample of mass ratio of 2/8 becomes smaller than the original sludge. This is because the sawdust reinforces the texture of sludge. Moreover, the volume shrinkage after drying becomes smaller with increasing addition of sawdust. Then the air and the sample contact more fully with more sawdust addition, resulting from bed expansion and exchange surface increase. Hence, the heat and mass transfer efficiency between the air and the material increases and consequently the drying rate increases. To sum up, the sawdust addition is beneficial to the sludge drying process. Further work will be done in order to assess the impact of the drying temperature and to characterize the pore texture of the samples. The behaviour of these samples during pyrolysis using thermo gravimetric analysis will also be investigated.

# References

ASAE, 1996 – ASAE Standard no. D245.5, American Society of Agricultural Engineers (Eds.), St. Joseph, MI, USA, pp. 452-464.

Bennamoun L., Crine M. and Léonard A., 2013 – convective drying of wastewater sludge: introduction of shrinkage effect in mathematical modelling, Drying Technology 31(6): 643-654.

Berghel J. and Renstrom R., 2002 – basic design criteria and corresponding results performance of a pilot-scale fluidized superheated atmospheric condition steam dryer, Biomass and Bioenergy 23: 103-112.

Deng W., Li X., Yan J., Wang F., Chi Y. and Cen K., 2011 – moisture distribution in sludges based on different testing methods, Journal of Environmental Sciences 23(5): 875-880.

Gac [J.M.](http://www.sciencedirect.com/science/article/pii/S0921883112001306) and Gradoń L., 2013 – a distributed parameter model for the spray drying of multicomponent droplets with a crust formation, Advanced Powder Technology 24(1): 324-330.

Huron Y., Salmon T., Blandin G., Crine M. and Léonard A., 2010 – effect of liming on the convective drying of urban residual sludges, Asia-Pacific Journal of Chemical Engineering 5(6): 909-914.

Lee D.J. and Liu J.C., 2004 – route to synthesize the sludge management processes, Water Science and Technology 49 (10): 259-266.

Léonard A., Meneses E., Le Trong E., Salmon T., Marchot, P., Toye D. and Crine M., 2008 – influence of back mixing on the convective drying of residual sludges in a fixed bed, Water Research 42(10–11): 2671-2677.

Léonard A., Blandin G. and Crine M., 2009 – importance of rheological properties when drying sludge in a fixed bed, 4th Inter-American Drying Conference: challenges for efficient drying processes, Montreal, Canada, pp. 258-263.

Schultz P. and Schlünder E.U., 1990 – influence of additives on crust formation during drying, influence of additives on crust formation during drying, Chemical Engineering and Processing: Process Intensification 28(2): 133-142.

Sherwood T.K., 1929 – the drying of solids – II, Industrial and Engineering Chemistry 21(10): 976-980.

Spinosa L., 2001 – evolution of sewage sludge regulations in Europe, Water Science and Technology 44 (10): 1-8.

Tao T., Peng X.F. and Lee D.J., 2005a – thermal drying of wastewater sludge: change in drying area owing to volume shrinkage and crack development, Drying Technology 23(3): 669-682.

Tao T. Peng X.F. and Lee D.J., 2005b – structure of crack in thermally dried sludge cake, Drying Technology 23(7): 1555-1568.

Toye D., Crine M. and Marchot P., 2005 – imaging of liquid distribution in reactive distillation packings with a new high-energy X-ray tomograph, [Measurement Science and Technology](http://iopscience.iop.org/0957-0233) 16(11): 2213-2220.

Vesilind P.A. and Spinosa L., 2001 – production and regulations, In: Spinosa, L., Vesilind P. A. (Eds.), Sludge into biosolids, Processing, Disposal and Utilization, IWA Publishing, London, pp. 3-18.