Computational modeling of biosludge drying

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Abstract

Considerable increases in industrial and urban wastewater sludge generation in recent years require proper treatment, such as thermal drying, and disposal. The sludge drying is a complex process involving simultaneous and coupled heat and mass transfer, which can be modeled by taking into account mass and heat balances, and assuming that water diffuses according to kinetic laws. This research implemented a simulation model for biosludge drying processes to predict the temperature and moisture distribution inside the biosludge, using the COMSOL Multiphysics® simulation program v5.2. A parametric analysis was carried out to determine the effect of initial moisture content on biosludge final temperature and moisture reduction. The simulated temperature and moisture content were experimentally validated and good agreement was observed between the simulation and experimental results. This model is a useful tool to optimize the drying process and develop better strategies for the control of the system.

Keywords: Biosludge drying; Heat and mass transfer; Modeling.

1. Introduction

Biosludge is a byproduct of industrial wastewater treatment plants usually disposed of in landfills, incinerated, applied in agriculture or incorporated into building materials (Putranto and Chen, 2014; Seggiani et al., 2012; Bennamoun, 2012). Biosludge represents a promising feedstock for energy processes due to its high organic content (Milhé et al., 2016; Otero et al., 2008; Zhou and Jin, 2016). For the treatment, usage and disposal of sludge, a low moisture content is both desirable and necessary (Deng et al., 2009; Stasta et al., 2006; Zhou and Jin, 2016). Mechanical dewatering processes currently employed in industry fails to achieve satisfactory moisture levels, and a drying step is often required. These drying processes are extremely important because a reduction in sludge volume and moisture content facilitates handling and transportation, as well as its use in combustion processes.

Drying implies removing moisture from natural or industrial materials to achieve a specific moisture content, while at the same time ensuring a prime quality product, high quantity and minimal operational costs (Defraeye, 2014).

The drying of sludges is a complex process involving simultaneous and coupled heat and mass transfer which is influenced by many factors such as operational conditions, the degree of hydration and the pore structure and physicochemical properties of the sewage sludge (Huang et al., 2016; Kaya et al., 2006; Salemovic et al., 2015). Such processes can be modeled by taking into account mass and heat balances, and assuming that water diffuses according to kinetic laws (Font et al., 2011).

The modeling principle is based on having a set of mathematical equations, which can adequately characterize the process, and the solution of these equations must allow the prediction of the process and moisture transfer parameters as a function of time (Hussain and Dincer, 2003).

Numerical modeling technology offers an efficient and powerful tool for simulating the sludge drying. The use of numerical methods such as finite difference, finite element and finite volume analysis to describe sludge drying has produced a large number of models. However, the accuracy of numerical models can further be improved by more information about the surface heat and mass transfer coefficients, sludge properties, volume change during processes and sensitivity analysis for justifying the acceptability of assumptions in modeling (Siqueira et al., 2018; Bisceglia et al., 2013).

Several drying models were proposed to describe sludge drying. Krawczyk and Badyda (2011) presented the key assumptions for a mathematical model which describes heat and mass transfer phenomena of a solar sewage drying process, as well as techniques used for solving this model with the Fluent computational fluid dynamics (CFD) software. Font et al. (2011) developed a mathematical model for the drying process of small sewage sludge spheres and cylindrical tablets, which considers the evaporation of water from the surface of the particle, the diffusion effects in sewage sludge due to heat and moisture and the formation of a skin layer. Milhé et al. (2016) presented the development of a model adapted to a continuous pilot-scale sludge paddle dryer by coupling Markov chains with penetration theory, leading to the simulation of water content and temperature profiles along the dryer during steady-state operations. Putranto and Chen (2014) investigated and evaluated the REA (reaction engineering approach) to model the convective drying of sewage sludge.

The objective of the present study was to implement a simulation model, based on experimental data, for biosludge drying processes using COMSOL Multiphysics® simulation program v5.2. The specific objectives were to predict the temperature and moisture content of the biosludge pile over time, and also provide a visualization of temperature and moisture distribution and evolution inside the biosludge.

2. Materials and Methods

2.1. Biosludge drying

The biosludge used in this study was obtained from an activated sludge effluent treatment plant of a paper mill, with the capacity to treat 720 $m^3.d^{-1}$ and generate 5 t.d-1 of biosludge with a solids content of 15% after dewatering in a centrifuge.

Figure 1 shows the experimental apparatus of the sludge drying system. Piles of biosludge were built over the aeration diffuser (Figure 3G), and a hot gas flow of (0.64 ± 0.02) $m^3.s^{-1}$ at a temperature of (100 ± 20)°C, provided by the direct coal-fired furnace, forcing its passage through the piles. The system operated during 5 hours. The initial mass, length and height of the piles were set to 150 kg, 2.0 m and 27 cm respectively.

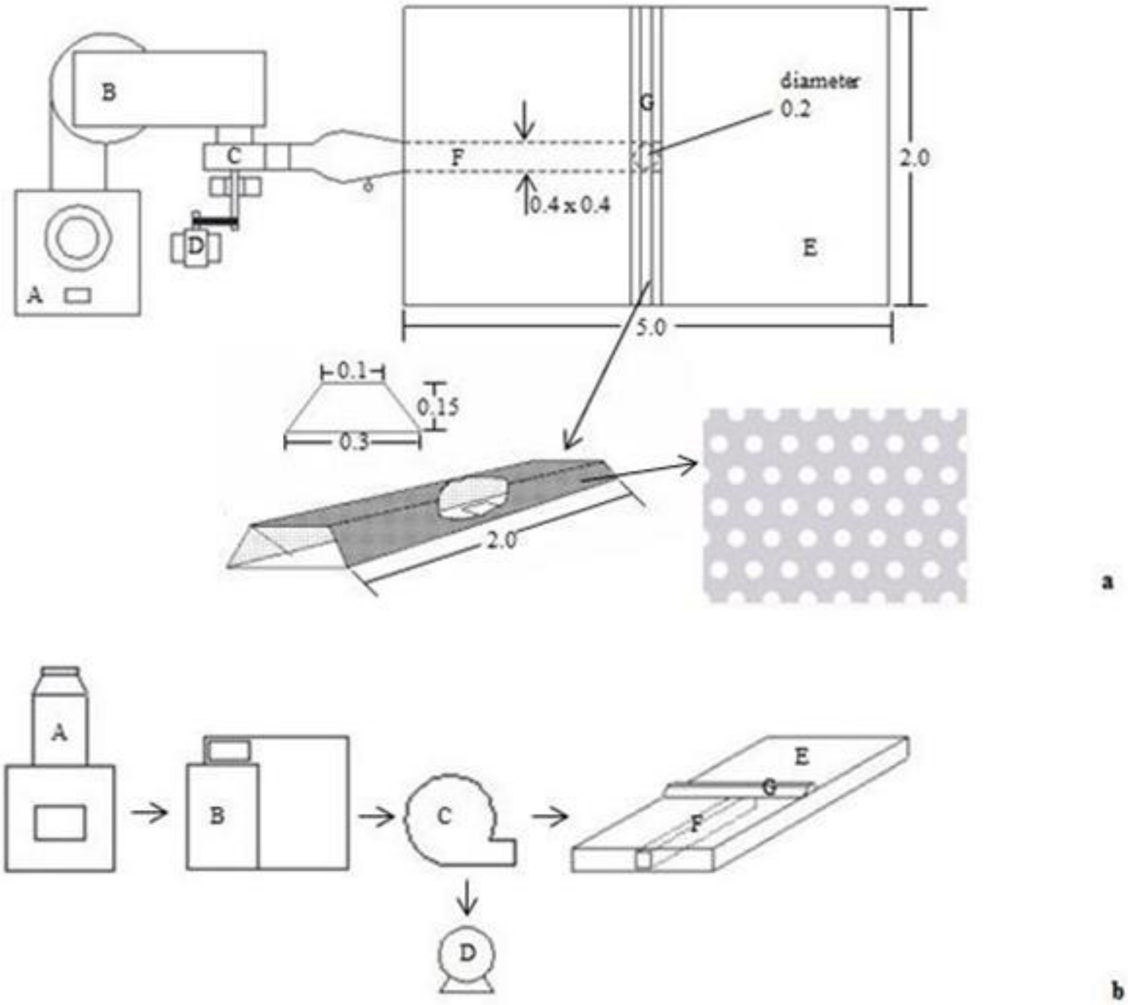

Figure 1. Drying system. (a) Plant and (b) flowchart: (A) direct fired coal furnace; (B) cyclone; (C) fan; (D) electric engine; (E) terrace; (F) distribution duct; (G) aeration diffuser.

During the drying system operation, the biosludge pile temperatures were measured at 15 points, every 30 minutes, using HIGHMED HM-600 thermometers, located 5cm deep at the top, middle and bottom of the pile. The moisture content was monitored at 15 points, every 60 minutes, using a moisture analyzer OHAUS MB45. These data were used in a comparison with the simulated results.

2.2. Model description

The proposed model is based on the heat and mass transfer through the biosludge pile. Both modes of transfer have an effect on each other and occur simultaneously during drying. Heat is transferred from the hot gas toward the pile center and from the pile surface into the atmosphere. Meanwhile, water diffuses outward toward the pile surface, and is evaporated. This model was solved using the Comsol Multiphysics® 5.2.

The geometry used in the simulations represents the biosludge pile, which was considered symmetrical. Figures 2 and 3 present the computational area and the mesh, respectively.

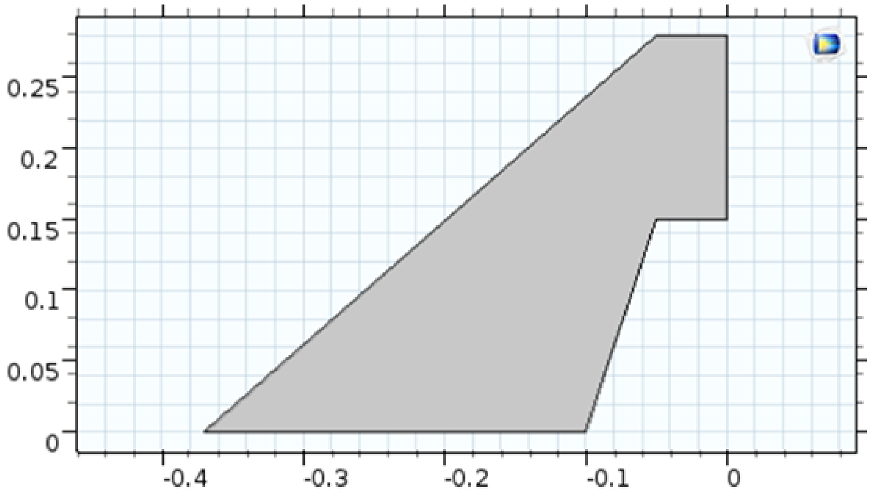

Figure 2. Geometry used in the simulation of sludge drying process.

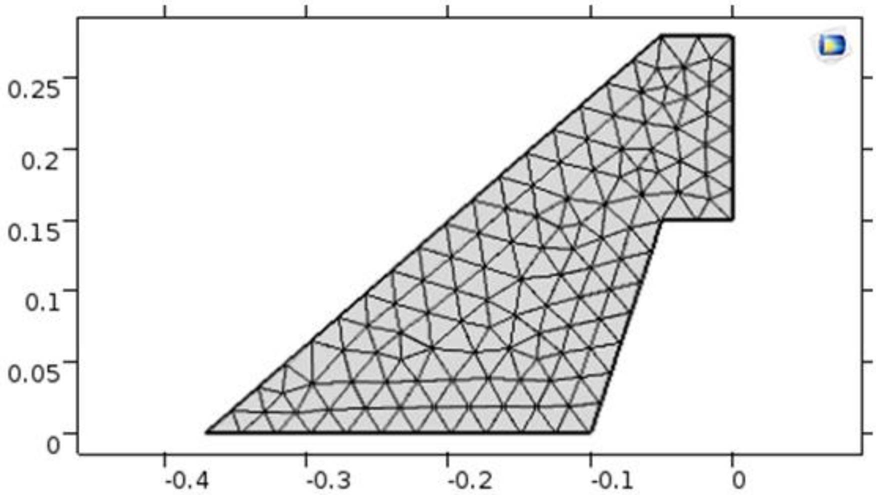

Figure 3. Mesh used in the simulation of sludge drying process.

The simulation was carried out in two-dimensions using the following assumptions: (i) constant thermophysical properties; (ii) negligible shrinkage or deformation of object during drying; (iii) evaporation occurs only at the surface of the pile; (iv) moisture consists of pure water; (v) initial temperature and moisture content distribution in the pile is uniform; (vi) biosludge pile is a solid material; (vii) volume reduction is due to the change of the moisture content, the solid mass remains constant.

The model was solved according to the flow chart illustrated in Figure 4.

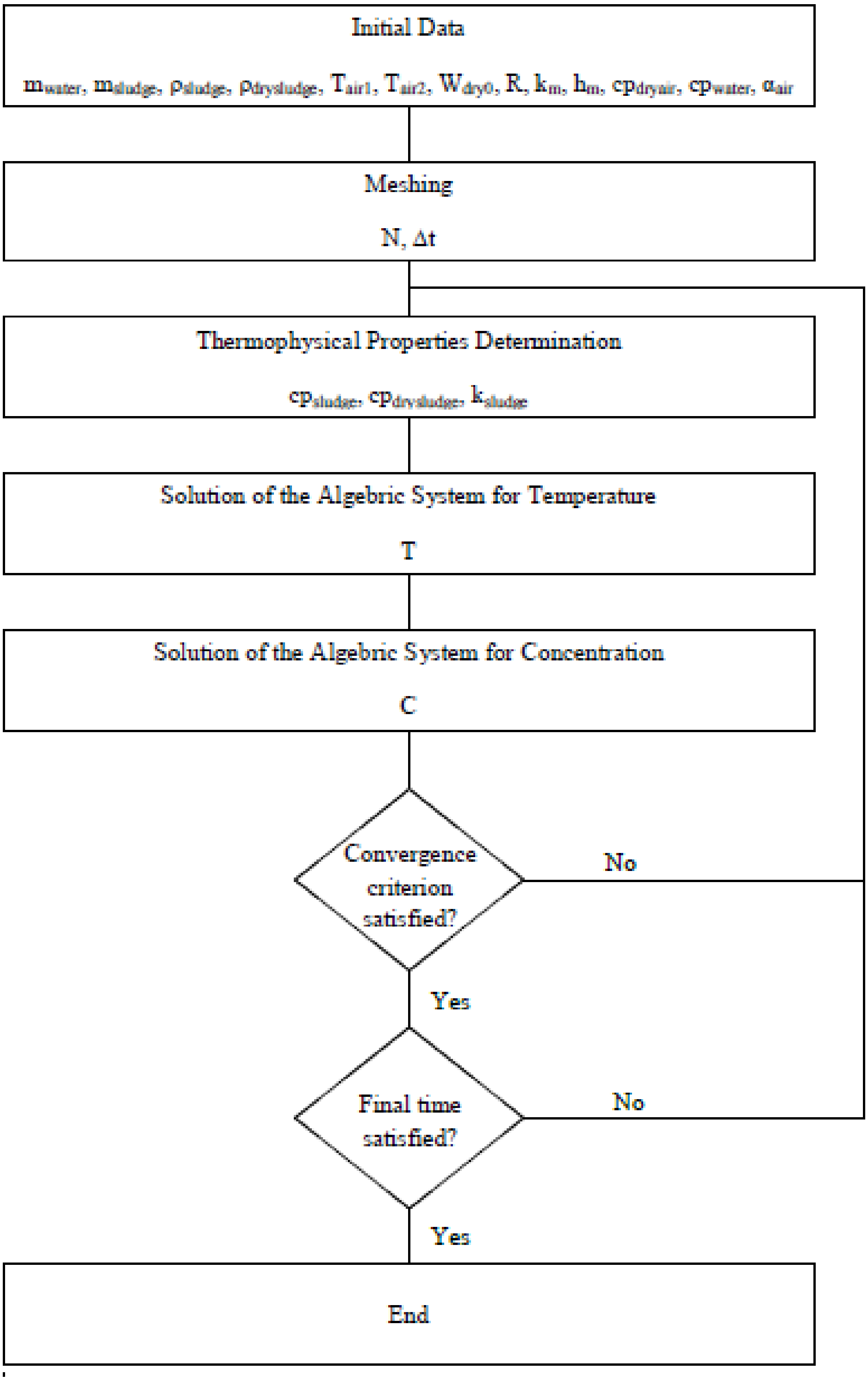

Figure 4. Numerical algorithm.

m_{water} = mass of water, m_{sludge} = mass of sludge, ρ_{sludge} = density of wet sludge, $\rho_{drysludge}$ = density of dry sludge, T_{air1} = output gas temperature (above), T_{air2} = input gas temperature (bellow), W_{dry0} = moisture in dry basis, R = universal constant, k_m = mass transfer coefficient, h_m = heat transfer coefficient, cp_{dryair} = specific heat capacity of dry air, cp_{water} = specific heat capacity of water, α_{air} = thermal diffusivity of air, N = number of elements, Δt = time, cp_{sludge} = specific heat capacity of sludge, $cp_{drysludge}$ = specific heat capacity of dry sludge, k_{sludge} = thermal conductivity of sludge, T = temperature, C = moisture concentration.

2.2.1. Governing equations

Based on the previous assumptions, the general heat and mass transfer equations (Equations 1 and 2, respectively) are as follow:

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T \tag{1}$$

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{2}$$

in which: ρ = pile density (kg.m^{-3}), c_p = specific heat of biosludge (J.kg^{-1}.K^{-1}), k = thermal conductivity of biosludge (W.m^{-1}.K^{-1}), T = pile temperature (K), C = pile moisture concentration (mol.m^{-3}), D = biosludge diffusivity (m^2.s^{-1}) and t = time (s). The boundary conditions for heat transfer at the surfaces (Equation 3), at the symmetry boundary (Equation 4) and at the internal boundaries (Equation 5) are:

$$k\nabla T = h(T_\infty - T) + h_{rad}(T_\infty - T) + D\lambda\nabla C \tag{3}$$

$$k\nabla T = 0 \tag{4}$$

$$k\nabla T = h\left(T_{gas} - T\right) \tag{5}$$

in which: h = convection transfer coefficient (W.m^{-2}.K^{-1}), h_{rad} = radiation transfer coefficient (W.m^{-2}.K^{-1}), T_∞ = air temperature (K), T_{gas} = gas temperature (K) and λ = molar latent heat of vaporization (J.mol^{-1}). The boundary conditions for mass transfer at the surfaces (Equation 6), at the symmetry boundary and internal boundaries (Equation 7) are:

$$D\nabla C = h_m(C_{air} - C) \tag{6}$$

$$D\nabla C = 0 \tag{7}$$

in which: h_m = mass transfer coefficient (kg.m^{-2}.s^{-2}) and C_{air} = air moisture concentration (mol.m^{-3}).
The initial conditions are:

$$T|_{t=0} = T_0 \tag{8}$$

$$C|_{t=0} = C_0 \tag{9}$$

in which: T_0 = initial pile temperature, equal to ambient temperature (K) and C_0 = initial pile moisture concentration (mol.m^{-3}).

2.3. Model validation

To validate the results of the numerical simulation, the obtained data for temperature and moisture content were compared with the experimental results. The simulation model performance was determined by calculation of root mean square error (RMSE), mean absolute error (MAE) and coefficient of determination (R^2).

$$RMSE = \sqrt{\frac{1}{n}\sum\left(\hat{Y}_i - Y_i\right)^2} \tag{10}$$

$$MAE = \frac{1}{n}\left|\frac{Y_i - \hat{Y}_i}{Y_i}\right| \tag{11}$$

$$R^2 = 1 - \frac{\sum\left(Y_i - \hat{Y}_i\right)^2}{\sum(Y_i - \overline{Y}_i)^2} \tag{12}$$

in which: RMSE = root mean square error, MAE = mean absolute error, R^2 = coefficient of determination, n = number of observations, Y_i = data obtained from the experiment, $\hat{Y}_i$ = data predicted by the simulation and $\overline{Y}_i$ = means of the data predicted by the simulation.

3. Results and Discussion

3.1. Experimental results

Figure 5 shows the moisture content and temperature variation into the biosludge pile. The hot gas temperature varied in the experiment from 80°C to 120°C, considering that the water in sludge can be removed by drying at temperatures around the water evaporation temperature (between 100°C and 105°C) (Bianchini et al., 2015).

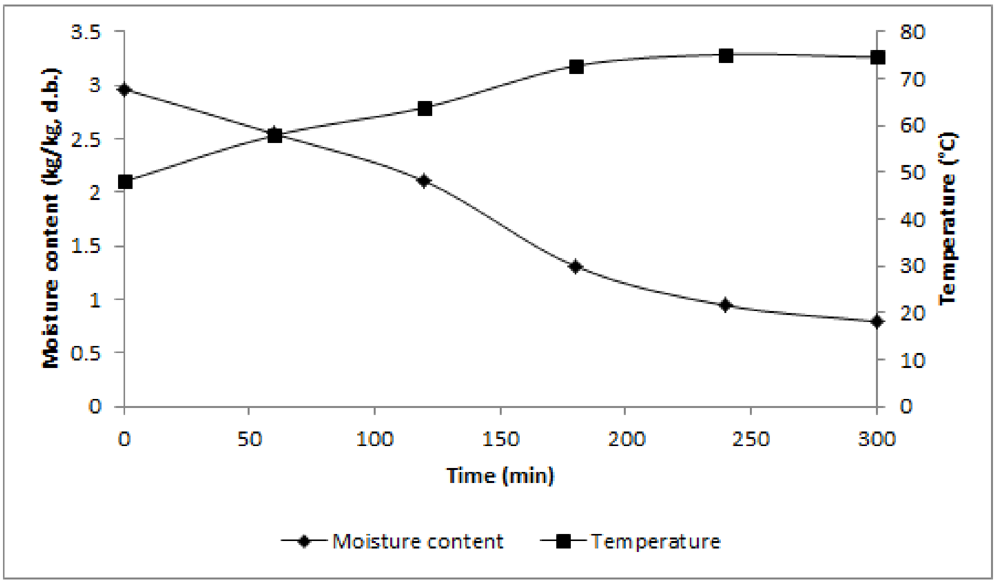

Figure 5. Moisture content and temperature profiles of biosludge pile

As the pile was placed in the drying chamber, heat from hot gas was rapidly directly transferred into sludge raising sludge sample temperature and evaporating water content, as well reported by Deng et al. (2009). The temperature of the pile increased in the beginning of the drying process and tended to a steady value, as observed by Huang et al. (2016) during hot air forced convective drying of sewage sludge, and Deng et al. (2009) evaluating sewage sludge in a paddle dryer. As shown in Figure 5 the moisture content reflects the amount of water evaporated during the biosludge drying and depends on the pile temperature.

The reduction of sludge moisture decreases the costs associated with sludge transportation and treatment and mostly increases significantly the low heating value of the sludge, turning it into a much better fuel.

At the end of drying, the moisture content of biosludge pile reached the minimum of 1 kg.kg^{-1} d.b. appropriated for combustion (Kraft and Orender, 1993; Werther and Ogada, 1999; Kudra et al, 2002; Frei at al. 2004). These values were similar to those found by Mäkelä et al. (2014) for the drying of recycled paper sludge using a high-velocity cyclone with air drying temperature of 90°C.

3.2. Computer simulation

Distributions of temperature and moisture concentration in biosludge pile after 5 hours are presented in Figures 6 and, respectively. As shown in Fig. 6, the biosludge immediately in contact with the drying gas reached the thermal equilibrium with the inlet gas, while the following layers had lower temperatures, since the gas loses enthalpy while ascending through the pile. This behavior was also observed by Pagano and Mascheroni (2013), during the drying of deep-bed amaranth grains. In Fig. 7, it can be seen how the moisture concentration decreased near the surface layer where the evaporation took place.

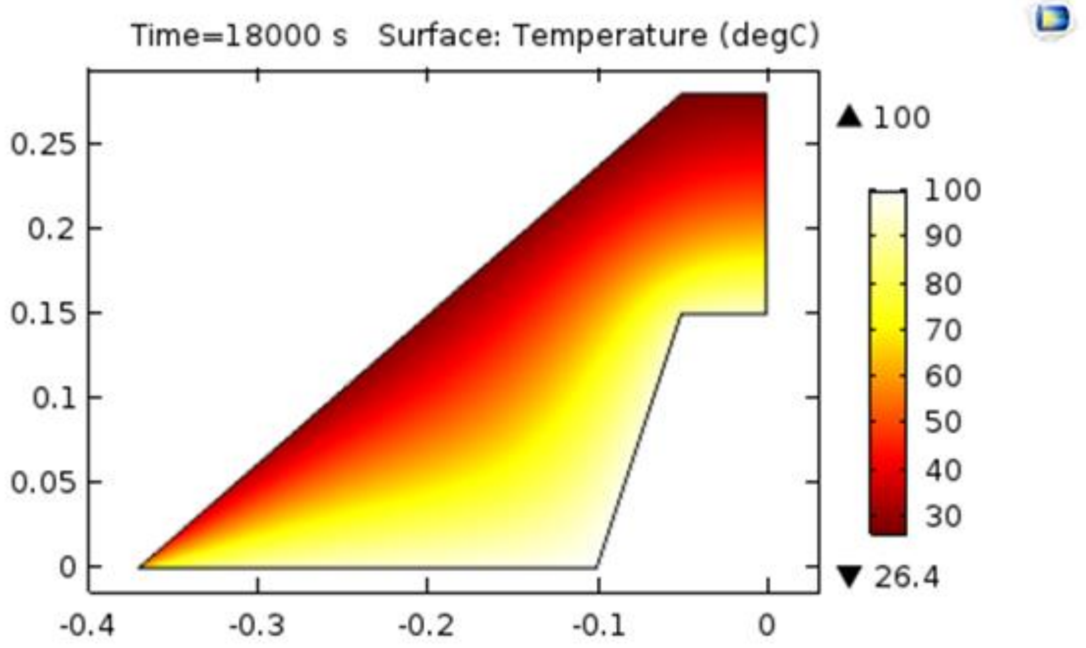

Figure 6. Temperature distribution in biosludge pile after 5 hours (18,000s) of drying.

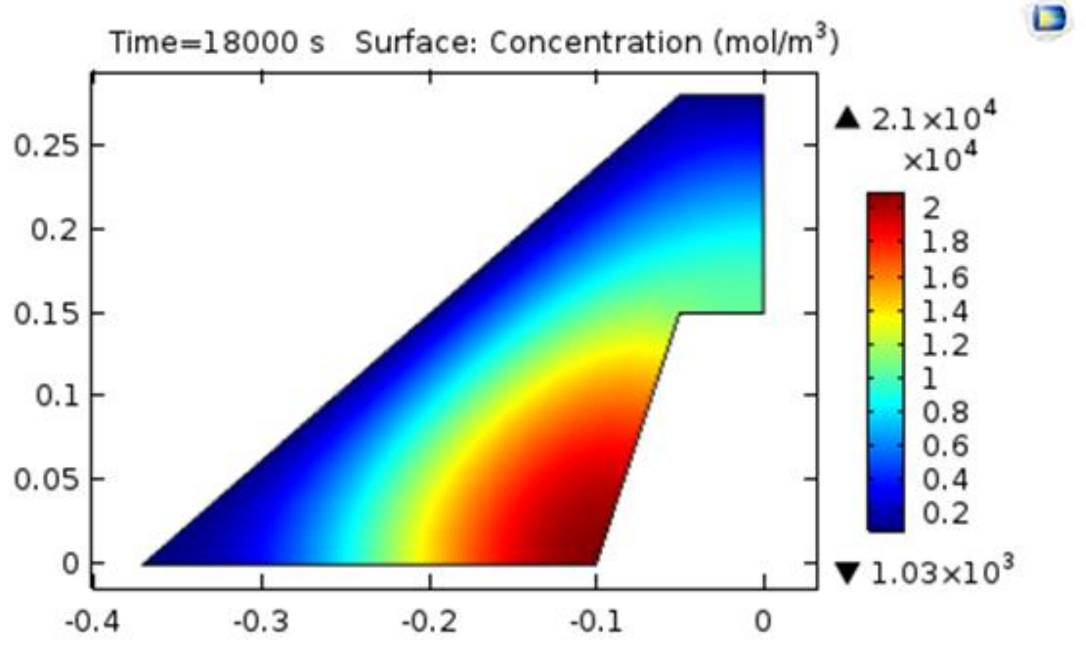

Figure 7. Moisture concentration distribution in biosludge pile after 5 hours (18,000s) of drying.

Figure 8 presents the temperature profile of the biosludge pile. The temperature increased gradually from ambient temperature to a maximum of 60°C. The temperature did not reach the gas temperature at the final drying period, because the water removal created pores in the biosludge pile, leading, according to Huang et al. (2016), to an increase in thermal resistance.

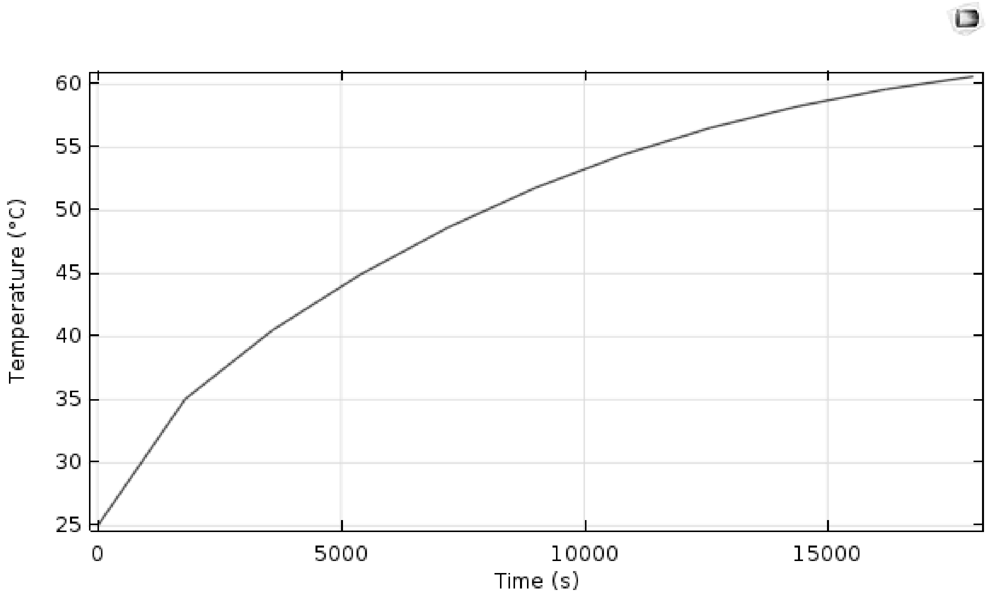

Figure 8. Temperature profile of biosludge pile.

Variation in the biosludge moisture content over time is shown in Figure 9. The biosludge moisture content decreased from 2.2 kg.kg^{-1} d.b. to 0.6 kg.kg^{-1} d.b. (dry basis) in 5 hours.

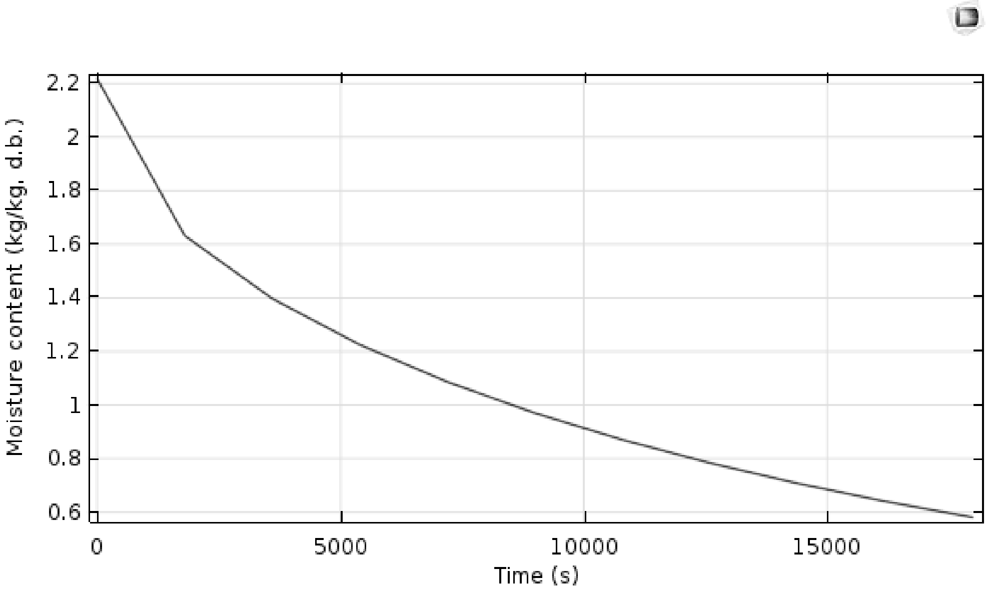

Figure 9. Moisture content profile of biosludge pile.

Figure 9 is one of the most important elements that give information about product behavior during drying (Bennamoun et al., 2013). It is observed that the drying process began with a short period where the moisture decreased rapidly due to the water evaporation from the pile surface. This period, known as the constant drying rate, took place in the first 30 minutes (1,800s) of drying, and the water evaporated was free water. During this phase, the evaporation is dominated by the rates of external heat and mass transfer since a film of free water is always available at the surface (Mujumdar and Devahastin, 2007; Li et al, 2016). So, the drying process only depended on the temperature, velocity and humidity of the drying gas, being independent of the biosludge character (Vaxelaire et al., 2000; Léonard et al., 2008). After 30 minutes of drying, the surface became poor in liquid, since, as explained by Huang et al. (2016), the evaporation rate of surface moisture was less than the diffusion rate of inner moisture in the biosludge pile, starting the first falling rate. When water evaporation began to decrease and slow down, after 4 hours (14,400s) of drying, the drying transitioned to the second falling drying rate. This was caused, according to Deng et al. (2009), by the diffusion of the moisture inside the biosludge structure. During the falling drying rates, the drying was governed by the rates of internal heat and mass transfer (Mujumdar and Devahastin, 2007; Li et al, 2016), with a decrease of the influence of external variables.

It can be seen in Figure 8 that the drying process occurred mostly in the falling rate periods, as stated by Bennamoun et al. (2013). According to Zhou and Jin (2016), this fact occurred because the moisture diffusion during drying was slow and mainly controlled by internal diffusion.

3.3. Comparison of temperature and moisture content profiles of experiment and simulation

Simulation results were compared with experimental data for temperature and moisture content profiles, as shown in Figure 10. According to RMSE (root mean square error), MAE (mean absolute error) and R^2 (coefficient of determination), both simulated temperature and moisture were in strong agreement with experimental data, even though the experimental temperature values were a little scattered. This comparison indicates that the model can predict temperature and moisture content quite accurately.

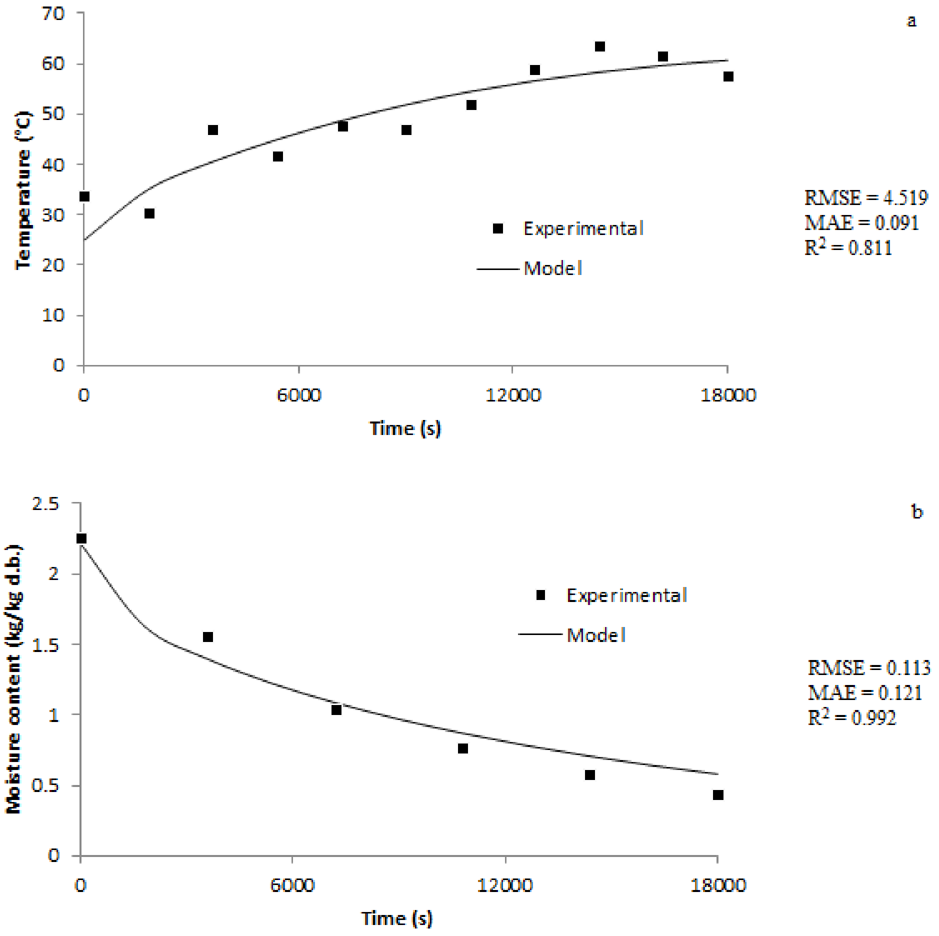

Figure 10. Temporal average (a) temperature and (b) moisture content profile obtained for experimental and simulation.

3.4. Parametric analysis

The validated model was used to investigate the influence of biosludge initial moisture content on final temperature and moisture reduction. Therefore, a parametric analysis was performed with different initial moisture contents, 9.0, 6.1, 4.6, 3.5, 2.8 and 2.3 kg.kg^{-1} d.b. The results are presented in Table 1.

Table 1. Effect of initial moisture on final temperature and moisture reduction.

Initial moisture content (kg.kg^{-1} d.b.)	**Final temperature (°C)**	**Final moisture content (kg.kg^{-1} d.b.)**	**Moisture reduction (kg.kg^{-1} d.b.)**	**Moisture reduction (%)**
9.0	63.12	0.73	8.26	92
6.1	62.87	0.70	5.40	88
4.6	62.45	0.67	3.92	85
3.5	61.84	0.64	2.86	82
2.8	61.22	0.61	2.19	78
2.3	60.64	0.58	1.72	75

It was observed that the increase in moisture content slightly increased the pile temperature. As verified by Deng et al. (2015), the sludge thermal conductivity decreases with moisture reduction and, since, according to Datta (2002) and Çengel (2006), the thermal conductivity is a measure of the efficiency of heat conduction, lower values led to less effective energy transport.

The increase in moisture content also increased the moisture reduction, with this fact being related to the biosludge diffusivity. Mass diffusivity represents the mobility of the water in the biosludge, and, according to Datta (2002) and Bergman et al. (2011) generally increases with moisture content. This is because more moisture is available for diffusion, and as the molecules become more mobile at higher temperatures, higher diffusivities also mean higher water evaporation and consequent moisture.

4. Conclusion

This study shows that it is possible to describe the thermal behavior of the biosludge during drying by using the simulation model proposed. The model, which takes into account the main phenomena of simultaneous heat and mass transfer, allows the prediction of biosludge temperature and moisture content during the drying period. The comparative study shows good agreement between simulated and experimental values of the biosludge temperature and moisture content during drying. Due to the cost and time involved in experimental studies, the simulation model is of great importance in the effective design and final adjustment and installation of the sludge drying equipment.

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