

# Influence of heating and moisture content on sludge drying process

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**Abstract.** Drying is one of the most efficient processes to reduce sludge volume by lowering moisture content. Vacuum filters are equipment suitable for sludge drying in small wastewater treatment plants. It is known that by reducing pressure in the filter, the vaporization process begins at lower temperature. The aim of this study is to estimate the values of liquid (free water) and gaseous (air) phase ratios in sludge cake during vacuum drying. Numerical results in function of heating temperature and cake initial moisture content are estimated by finite element analysis in a central point situated on cake surface.

## 1. Introduction

Wastewater sludge processing by dewatering has many advantages as: increasing its calorific value, lowering transport and storage costs, making sludge hygienic or improving its structure in case of agricultural use [1-5]. Applied dewatering techniques comprise natural methods using drying platforms and sludge lagoons, or mechanical ones carried out by filtration, centrifugation or thermal drying [3], [4], [6]. Thermal drying processes may be performed using convective, conductive or solar installations. Convective dryers transports hot air through the sludge mass in order to evaporate the water. Equipment using this technique are: belt dryer, flash dryer, fluidized bed dryer and rotary dryer [3], [4], [6]. Conductive sludge dryers such as disc dryer, paddle dryer or thin film dryer, use surface heat to warm the sludge in order to reduce water content [3], [4], [6]. Solar equipment uses greenhouse effect of direct solar radiations to heat and evaporate the sludge water [6].

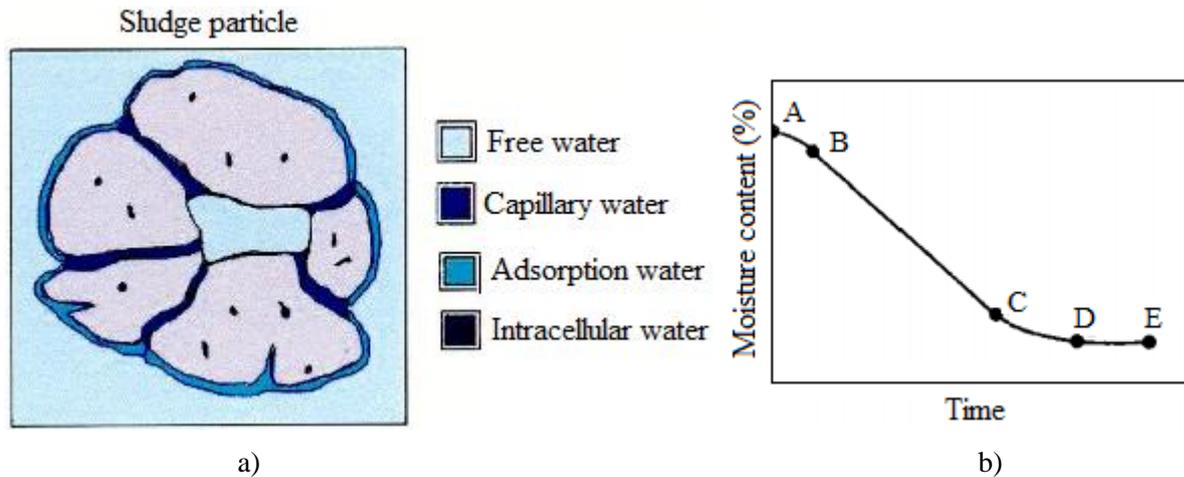
Regardless the technique, during thermal processing sludge mass and volume decreases as a result of water removal by evaporation, sludge moisture (water) being converted in a gaseous phase (air) [1-4]. In sludge, four forms of water are distinguished: *free water* (about 70% from the liquid phase), *capillary* and *adsorbed water* (22%) and *intracellular* water (8%), Figure 1.a [4], [5].

Free water is firstly and easy eliminated by gravitational or flotation processes. Capillary and adsorbed water need supplementary forces to be removed from solids surface, assured by filtration or centrifugal processes. Intracellular water can be removed from sludge solid particles by thermal processes [3-5].

The evaporation of free water from a solid bed is represented in Figure 1.b [1], [2] showing the decreasing in moisture content with drying time. Four stages may be observed [1-4], [6]. In the initial drying stage named *constant rate period*, represented by AB line, the free water is rapidly removed, because the sludge surface evaporation rate equals the rate with which the water inside the material diffuses to the surface. Follows the *first falling rate period* (BC line) where drying rate decrease because the sludge internal moisture diffusion rate is lower than the surface evaporation rate. In the *second falling rate period* (CD curve) the evaporation rate decreases progressively. In the two last



stages interstitial and respectively surface water is removed. Finally, at the end of the process there is a short interval (DE line) where the bounded water is removed [1-4], [6].



**Figure 1.** Forms of water contained in sludge cake (a) and typical drying curve (b) [1], [5]

This study aims estimating by finite element analysis of liquid and gaseous phase ratios during vacuum drying of a sludge cake up to 30 hours. Numerical results are determined in function of heating temperature, drying time and cake initial moisture content.

## 2. Equations governing drying process of sludge

Sludge cake contains beside a solid phase, a liquid (water) and a gaseous one (air) [7]. In order to characterize drying process of a sludge cake, governing equations of evaporation process and heat transfer must be coupled [7-9].

### 2.1. Evaporation of liquid phase

➤ *Liquid phase ratio*  $\theta_L$  can be evaluated using the following mass balance equation expressing variation of liquid phase ratio with drying time [7], [8]:

$$\frac{\partial \theta_L}{\partial t} = \nabla \cdot (D_L \cdot \nabla \theta_L) - \frac{m_{LG}}{\rho_L} \quad (1)$$

where  $D_L$  ( $m^2/s$ ) is the diffusion coefficient of the liquid phase, calculated with:

$$D_L = \alpha \cdot (\theta_L - \theta_L^*) \text{ if } \theta_L > \theta_L^* \quad (2)$$

for estimations residual saturation is considered  $\theta_L^* = 5\%$  and proportionality constant  $\alpha = 1,6 \cdot 10^{-7} m^2/s$ . The rate of water loss ( $m_{LG}$ , in  $kg/(m^3 \cdot s)$ ) depends on difference between the equilibrium vapor pressure of the liquid phase ( $p^*$ ) and the actual vapor pressure of air in the tank ( $p_G = 15$  mbar) by the relation [7], [8]:

$$m_{LG} = k_{vap} \cdot \rho_L \cdot (p^* - p_G) / p_G \text{ if } \theta_L > 0 \quad (3)$$

where  $k_{vap} = 1 \cdot 10^{-6} s^{-1}$  is the rate constant and  $\rho_L = 1000 kg/m^3$  is the liquid phase (water) density. The equilibrium vapor pressure of the liquid phase, which is temperature dependent (T), can be estimated using Antoine equation [7], [8]:

$$p^* = 10^{A - \frac{B}{C+T}} \quad (4)$$

where for temperature range 0-100°C, the values of constants are:  $A = 8.07131$  mmHg;  $B = 1730.63$  K;  $C = 233.426$  K [10], [11]. To convert coefficient A from (mmHg) to (Pa) the following relation is used [10]:

$$A_{(Pa)} = A_{(mmHg)} + \log_{10} \frac{101325}{760} = A_{(mmHg)} + 2.124903 = 10.196 Pa \quad (5)$$

➤ *Gaseous phase ratio*  $\theta_G$  can be evaluated considering that the sum of cake constituent phases ratios (solid, liquid and gas) equals unity [7], [8]:

$$\theta_G = 1 - (\theta_L + \theta_S) \quad (6)$$

### 2.2. Heat transfer in sludge cake

Energy balance equation in the cake (liquid and solid) is [7], [8]:

$$\rho_{eff} \cdot c_{p,eff} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_{eff} \cdot \nabla T) + Q \quad (7)$$

where density ( $\rho$  in  $\text{kg/m}^3$ ), specific heat capacity ( $c_p$  in  $\text{kJ}/(\text{kg}\cdot\text{K})$ ) and thermal conductivity ( $\lambda$  in  $\text{W}/(\text{m}\cdot\text{K})$ ) are calculated considering constitutive phases [7], [8]:

$$\rho_{eff} = \theta_L \cdot \rho_L + \theta_S \cdot \rho_S + \theta_G \cdot \rho_G \quad (8)$$

$$c_{p,eff} = (\theta_L \cdot \rho_L \cdot c_{p,L} + \theta_S \cdot \rho_S \cdot c_{p,S} + \theta_G \cdot \rho_G \cdot c_{p,G}) / \rho_{eff} \quad (9)$$

$$\lambda_{eff} = \lambda_{dry} + \frac{\theta_L}{1-\theta_S} (\lambda_{wet} - \lambda_{dry}) \quad (10)$$

Initial values considered for estimations are: density ( $\rho_G=1.29 \text{ kg/m}^3$ ,  $\rho_L=1000 \text{ kg/m}^3$ ,  $\rho_S=1400 \text{ kg/m}^3$ ), specific heat capacity ( $c_{p,G}=1.29 \text{ kJ}/(\text{kg}\cdot\text{K})$ ,  $c_{p,L}= 4.186 \text{ kJ}/(\text{kg}\cdot\text{K})$ ,  $c_{p,S}=4.18 \text{ kJ}/(\text{kg}\cdot\text{K})$ ) and thermal conductivity of dry and wet cake ( $\lambda_{dry}=0.134 \text{ W}/(\text{m}\cdot\text{K})$ ,  $\lambda_{wet}=0.1 \text{ W}/(\text{m}\cdot\text{K})$ ) [11].

In equation (7),  $Q$  in (W) is the heat source given by [7], [8]:

$$Q = -m'_{LG} \cdot \Delta H_{vap} \quad (11)$$

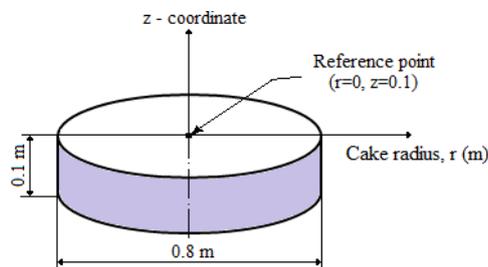
where  $\Delta H_{vap}=9703 \text{ cal/mol}$  [11] is the latent heat of vaporization. In the sludge cake volume heat is transmitted by conduction.

The heat needed for evaporation process is assured by a heating fluid circulating through side and bottom walls of vacuum filter. So, a convective heat transfer process takes place between heated filter wall and cake surface, considered convection heat transfer coefficient being of  $h=10 \text{ W}/(\text{m}^2\cdot\text{K})$ .

### 3. Results and discussions

Numerical results obtained by solving equations (1) and (7) by finite element method evaluate the liquid and gaseous phase ratios after 30 hours of drying in a vacuum filter. The operating drying process variables were: heating temperature ( $T_h = 60^\circ\text{C}$ ,  $80^\circ\text{C}$ ,  $100^\circ\text{C}$ ) and initial moisture content ( $w_{L0} = 20\%$ ,  $30\%$ ,  $40\%$ ) with corresponding solid phase ratios:  $\theta_S = 70\%$ ,  $60\%$ ,  $50\%$ . Initial sludge cake temperature was of  $20^\circ\text{C}$ .

The analysis domain is of cylindrical shape with diameter of  $0.8 \text{ m}$  and height of  $0.1 \text{ m}$  (Figure 2). So, the sludge cake occupies in the cylindrical filter a volume of  $0.05 \text{ m}^3$  (50 liters). Giving the cylindrical shape of analysis domain, the geometry was created in 2D axisymmetric space dimension enabling solution for half geometry along a symmetric vertical axis to reduce the modelling time. By employing a triangular mesh with extra fine element size, the modelled geometry was discretized in 1622 elements.



**Figure 2.** Analysis domain indicating reference point of coordinate  $r=0$ ,  $z=0.1 \text{ m}$

Results of the two phase ratios are given in function of heating temperature and initial moisture content estimated in a reference point of coordinate  $r=0$ ,  $z=0.1 \text{ m}$  (Figure 2).

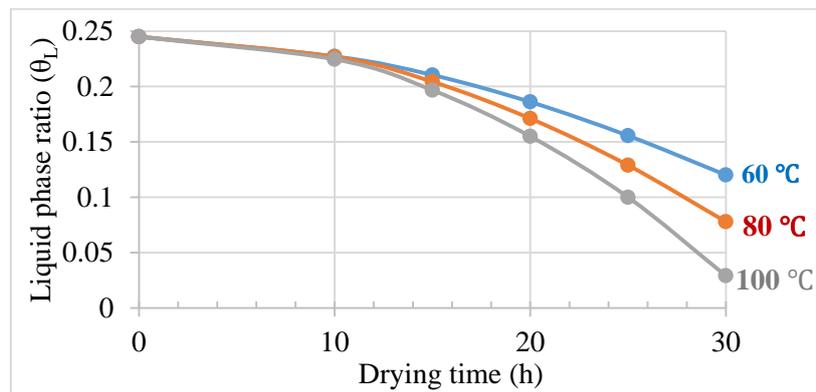
#### ➤ Liquid phase ratio estimations

The initial value of liquid phase ratio (before drying process commence) may be estimated in function of solid phase ratio ( $\theta_s$ ), solid phase density ( $\rho_s$ ), liquid phase density ( $\rho_L$ ) and initial moisture content ( $w_{L0}$ ) with relation [7], [8]:

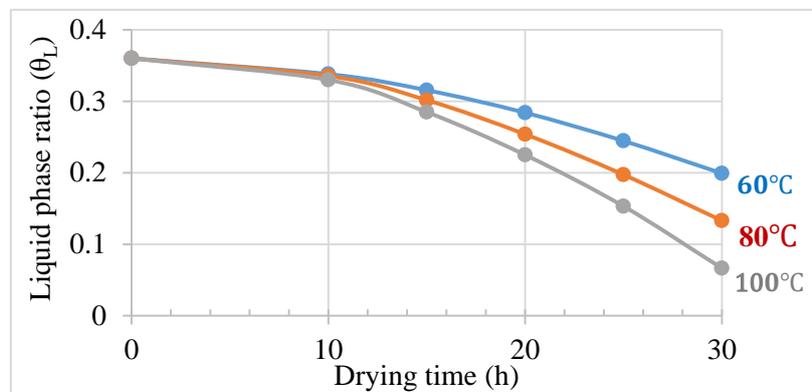
$$\theta_{L0} = \theta_s \cdot \frac{\rho_s}{\rho_L} \cdot \frac{w_{L0}}{1-w_{L0}} \quad (12)$$

So, for the three considered scenarios, the estimations are: a)  $\theta_{L0} = 0.7 \cdot \frac{1400}{1000} \cdot \frac{0.2}{1-0.2} = 0.245$ ; b)  $\theta_{L0} = 0.6 \cdot \frac{1400}{1000} \cdot \frac{0.3}{1-0.3} = 0.360$ ; c)  $\theta_{L0} = 0.5 \cdot \frac{1400}{1000} \cdot \frac{0.4}{1-0.4} = 0.466$ .

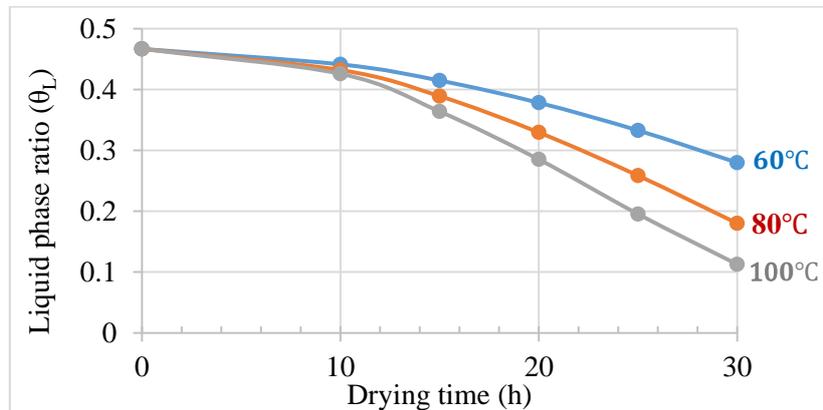
Figures 3-5 presents the variation of liquid phase ratio  $\theta_L$  in function of drying time and heating temperature for cake initial moisture content of 20%, 30% and 40% respectively.



**Figure 3.** Variation of liquid phase ratio  $\theta_L$  in function of drying time and heating temperature for cake initial moisture content of  $w_{L0} = 0.2$



**Figure 4.** Variation of liquid phase ratio  $\theta_L$  in function of drying time and heating temperature for cake initial moisture content of  $w_{L0} = 0.3$



**Figure 5.** Variation of liquid phase ratio  $\theta_L$  in function of drying time and heating temperature for cake initial moisture content of  $w_{L0} = 0.4$

In all cases presented in Figures 3-5 it may be observed a continuous decreasing of  $\theta_L$  ratio with increasing drying time and heating temperature. In none of the estimations the liquid phase attends zero value associated with dry cake. It is known that evaporation process is complete when liquid phase ratio is zero, or vapor pressure of liquid phase is smaller than partial pressure of air above cake surface [3].

Instead, it is observed that after 30 hours of drying at all temperatures, the liquid phase ratio value is favored by initial moisture content, as the  $\theta_L$  values are the smallest for  $w_{L0} = 0.2$ . So, the estimated values of  $\theta_L$  for cake initial moisture  $w_{L0} = 0.2$  (Figure 3),  $w_{L0} = 0.3$  (Figure 4) and  $w_{L0} = 0.4$  (Figure 5) after 30 hours of drying at 100°C, are about 3%, 6.7% and 11.2% respectively.

Also, calculating the proportion between initial and final (after 30 hours of drying)  $\theta_L$  values, for heating temperature of 100°C, it is found that the liquid ratio is eliminated in proportion of 88.12% for  $w_{L0} = 0.2$  (Figure 3), 81.53 % for  $w_{L0} = 0.3$  (Figure 4) and 75.84% for  $w_{L0} = 0.4$  (Figure 5), indicating the influence of initial moisture content of sludge cake.

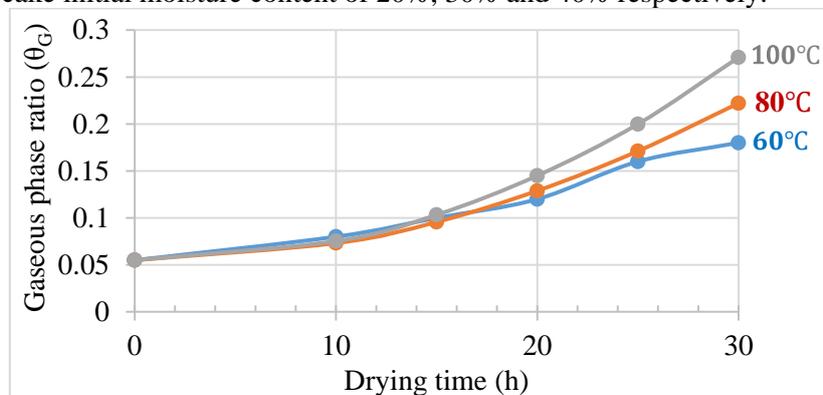
➤ *Gaseous phase ratio estimations*

Gaseous phase ratio value also may be estimated initially, before drying process commence, considering that the ratios sum of the three phases comprises in sludge cake equals unity [7], [8]:

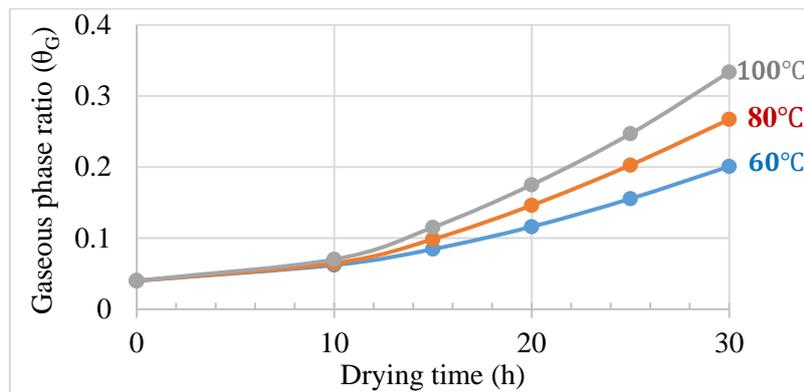
$$\theta_G = 1 - (\theta_{L0} + \theta_S) \quad (13)$$

So, for the three considered scenarios, the estimations are: a)  $\theta_G = 1 - (0.245 + 0.7) = 0.055$ ; b)  $\theta_G = 1 - (0.360 + 0.6) = 0.040$ ; c)  $\theta_G = 1 - (0.466 + 0.5) = 0.034$ .

Figures 6-8 presents the variation of gaseous phase ratio  $\theta_G$  in function of drying time and heating temperature for cake initial moisture content of 20%, 30% and 40% respectively.

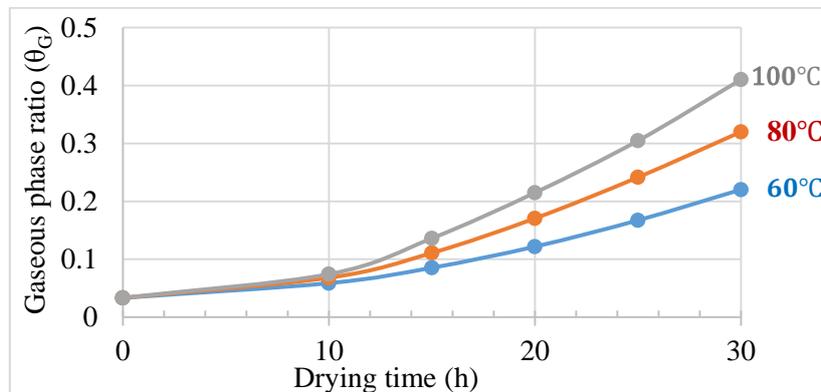


**Figure 6.** Variation of gaseous phase ratio  $\theta_G$  in function of drying time and heating temperature for cake initial moisture content of  $w_{L0} = 0.2$



**Figure 7.** Variation of gaseous phase ratio  $\theta_G$  in function of drying time and heating temperature for cake initial moisture content of  $w_{L0} = 0.3$

As sludge cake dries and the liquid phase (free water) evaporates, the spaces between solid particles is replaced by gaseous phase (air). In estimations from Figures 6-8 it is observed the gaseous phase ratio value increase with increasing drying time and heating temperature. Also, in scenarios considering higher heating temperature, the  $\theta_G$  ratio is bigger. Also, calculating the proportion between final (after 30 hours of drying) and initial  $\theta_G$  values, for heating temperature of 100°C, it is found that the gaseous phase ratio increases with 79.7% for  $w_{L0} = 0.2$  (Figure 6), 88 % for  $w_{L0} = 0.3$  (Figure 7) and 91.7% for  $w_{L0} = 0.4$  (Figure 8).



**Figure 8.** Variation of gaseous phase ratio  $\theta_G$  in function of drying time and heating temperature for cake initial moisture content of  $w_{L0} = 0.4$

Concerning the optimal operation conditions and taking into account that vacuum dryers operate at temperatures up to 150°C [4], in the analyzed scenarios, temperature of 100°C may be recommended.

#### 4. Conclusions

Estimations by finite element analysis of liquid and gaseous phase ratios after 30 hours of drying in a vacuum filter are evaluated in function of different heating temperatures (60°C, 80°C and 100°C) and initial moisture content (20%, 30% and 40%). Quantitative results showed that efficiency of drying process is obtained at small initial moisture content of sludge cake and high heating temperature. The obtained results can be useful in determining the optimum operation conditions, or for dimensioning vacuum filters [7].

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