Analysis of wastewater sludge drying process in vacuum filters

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Abstract. The paper presents a case study on wastewater sludge drying in a vacuum filter. Using finite element analysis it is estimated the variation with cake height, along its centerline, of temperature, liquid and gaseous phase ratios. Numerical results are estimated after 30 hours of drying at different temperatures (60ºC, 80ºC and 100ºC), considering a sludge initial moisture content of 20%.

1. Introduction

Processes conducted in wastewater treatment plants lead to a significant part retention of pollutants as sludge. So, wastewater treatment plants comprises equipment and installations for [1]:

- *primary and secondary wastewater treatment* which aims to comply with effluent quality conditions according to regulations (NTPA 001/2002), before discharging it into rivers;

- *sludge processing* for ease its manipulation and storage or even its transformation into economically exploitable substances for agriculture, energy production or building materials.

One of the purposes of sludge processing is to reduce its volume. This may be achieved by decreasing the moisture content [1]. Methods of sludge processing include operations as: thickening, stabilization, conditioning or drying [1-3]. Sludge drying can be done by: natural (drying platforms, sludge ponds), thermal (incineration furnaces) or mechanical processes [1-3]. Also, the mechanical processes can be achieved by centrifugation (centrifuges and centrifugal sites) and by filtration (frame press filters, belt press filters, vacuum filters) [1-3].

Vacuum filters are available in a large number of designs, having the possibility to perform pressure or vacuum filtration, heating or cooling the charge [2]. Also named Nutsche filters, these equipment have many applications in dye, paint, pharmaceutical production or wastewater treatment [3].

In Figure 1.a [2] is presented the schematic of a vacuum filter composed of an enclosed cylindrical tank with a horizontal filter plate (fabric, metal plate) at the bottom. Processes occurring during sludge drying in a vacuum filter are [2], [3]:

- *Charging the sludge*. This operation is done at the top, by gravity or a sludge pump. Maximum cake thickness is 1 meter. After sludge feed is complete, pressure drop is achieved which is the driving force for filtration.

- *Filtration*. By using suction of air on the bottom side of the filter plate, filtrate (free water from sludge) is forced passing through the plate, being collected at the filter bottom.

- *Sludge cake drying*. The solid phase (cake) retained on the porous filter plate surface is dried by a heating liquid flowing through the outer shell of the filter.

- *Cake discharge*. It is done by means of the valve in the tank side wall. By rotating the stirrer it moves the cake toward lateral discharge valve.

Researchers have analyzed sludge thermal drying process by experimental studies [4-6] or by modeling approaches [4], [7-9]. In drying models is assumed that cake constituent phases are: solid particles of impurities, liquid phase (free water) and gaseous phase (air which replaces the liquid phase during vaporization). The evaporation process is characterized by an exchange of mass (liquid phase diffusion in sludge due to a moisture gradient along cake height) and heat phenomena (conduction heating of sludge solid and liquid phases). External heat may be transferred to cake surface by convection or radiation [4], [5], [8-10].

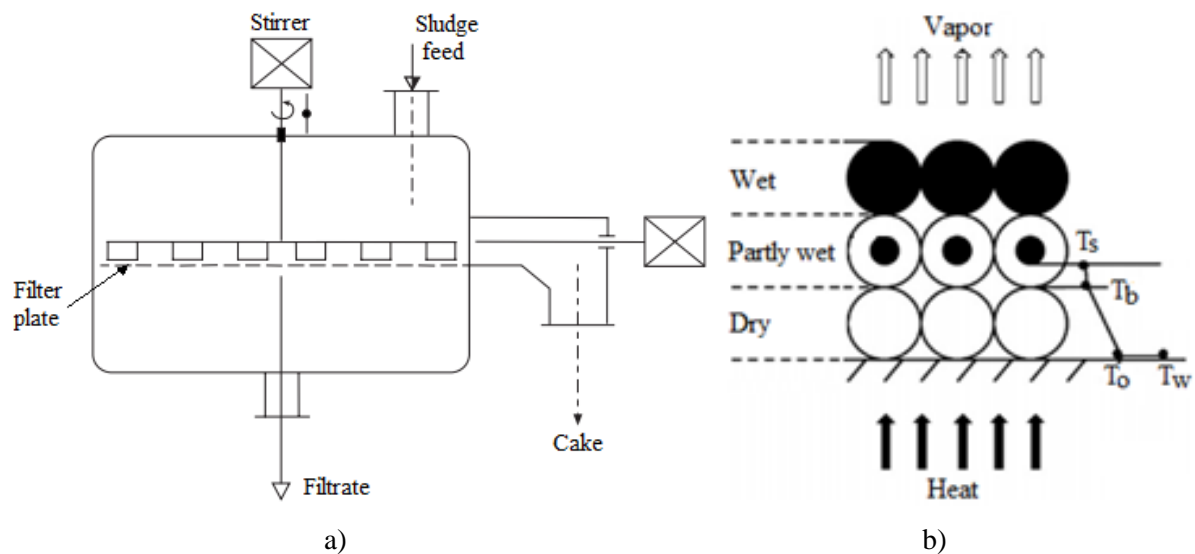In Figure 1.b [4] is shown temperature distribution in a granular sludge cake heated from below.

a) b)

Figure 1. Schematic representation of a vacuum-filter (a) and temperature distribution in a granular sludge cake heated from below (b) [2], [4]

As filter walls are heated from bottom up to a temperature T_w, first stage of sludge cake drying is increasing bottom surface temperature up to a certain constant temperature T_0. Follows a longer drying stage in which free water (water between solid sludge particles) and surface water (adsorbed on sludge particles) evaporates with a constant rate. As evaporation develop at sludge particles surface, capillary water (from inside of the particle) emerge to particle surface. This stage develops at constant temperature T_s (about 50-85ºC) equal to free water temperature T_b [4], [5].

This paper aims estimating by finite element analysis of temperature, liquid phase ratio and gaseous phase ratio of a sludge cake dried in a vacuum filter during 30 hours. Considering the sludge initial moisture content of 20%, numerical results are determined at different temperatures in function of cake height (along cake centerline, r=0).

2. Case study. Results and discussions

This case study refers to a sludge cake of cylindrical shape with 0.8 m diameter and 0.1 m thickness dried in a vacuum filter during 30 hours. The cake constituent phases are: solid particles of impurities, liquid phase (free water) and gaseous phase (air) [8], [10]. Cake initial moisture content is considered of 20%.

A schematic representation of the analysis domain is given in Figure 2. Cake surface is in contact with a pressure drop space of 15 mbar, while bottom and side walls are heated by fluid flowing through the outer shell of the filter. Three different heating temperatures are considered: 60ºC, 80ºC and 100ºC. In all cases cake initial temperature was of 20ºC. By operating at a very low pressure and

at a high temperature, the evaporation rate increases, thereby accelerating the sludge cake drying process [8], [9].
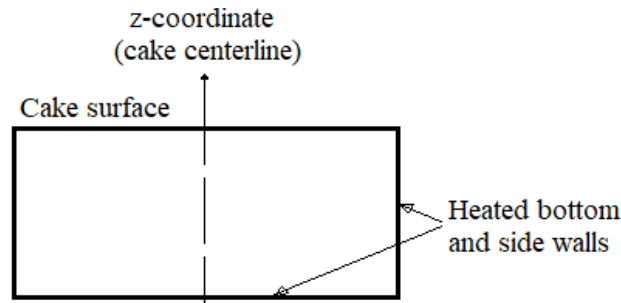

Figure 2. Schematic representation of the analysis domain

The vacuum drying process involves two processes: conduction heat transfer through cake volume and evaporation of the liquid phase. So, drying of porous media (i.e. wet cake) may be described by partial differential equations of these phenomena, given in references [8-10]. The considered parameters required to solve characteristic equations by finite element method in this study, are [11], [12]: parameters in Antoine equation (A=10.196; B=1690.864; C=233.426); proportionality constant for apparent diffusion coefficient ($\alpha=1{,}6 \cdot 10^{-7}$ m^2/s); latent heat of evaporation ($\Delta H=9703$ cal/mol); evaporation rate constant ($k_{vap}=1 \cdot 10^{-6}$ 1/s); convection heat transfer coefficient (h=10 W/(m^{2}K)); specific heat capacity of gas, liquid and solid phases ($c_{p,G}=1.29$ kJ/(kg·K), $c_{p,L}=4.186$ kJ/(kg·K), $c_{p,S}=4.18$ kJ/(kg·K)); thermal conductivity of dry and wet cake ($\lambda_{dry}=0.134$ W/(m·K), $\lambda_{wet}=0.1$ W/(m·K)); density of gaseous, liquid and solid phase ($\rho_G=1.29$ kg/m^3, $\rho_L=1000$ kg/m^3, $\rho_S=1400$ kg/m^3).

Numerical results of temperature variation versus cake height (z-coordinate) after 30 hours of drying at different heating temperatures (T_h) are given in Figure 3.
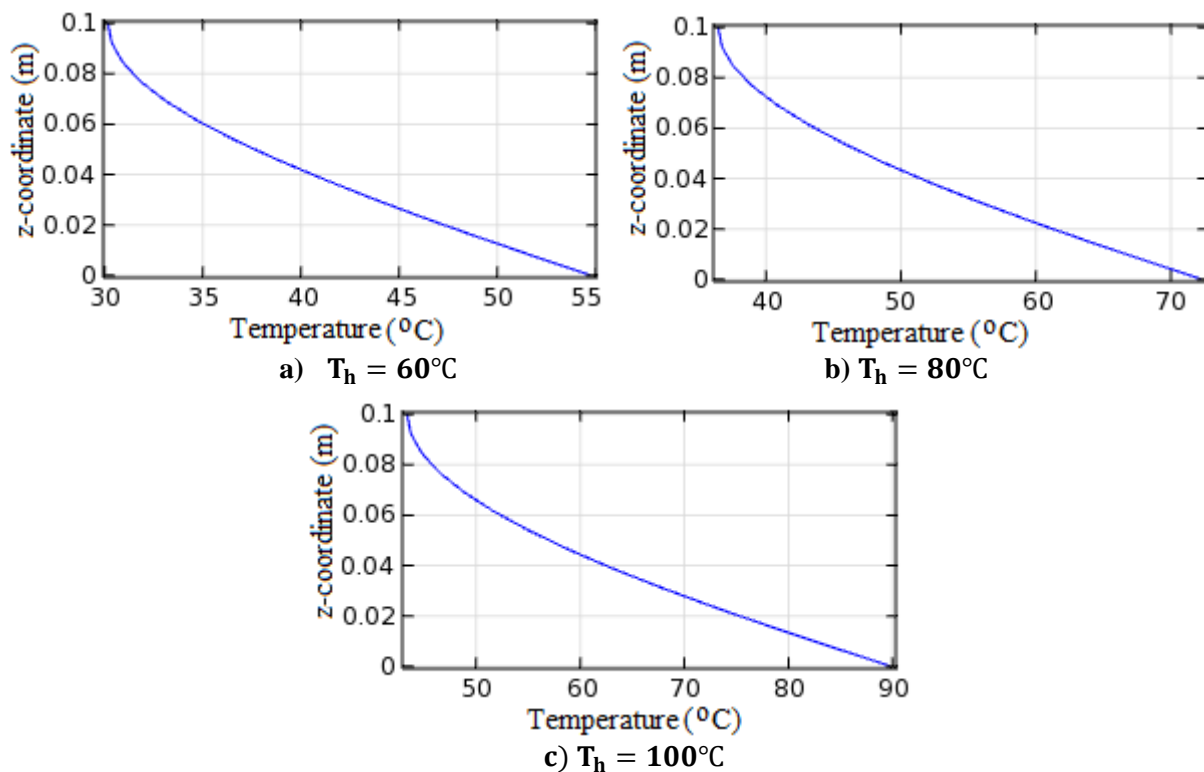

a) $T_h = 60°C$

b) $T_h = 80°C$

c) $T_h = 100°C$

Figure 3. Variation of temperature in sludge cake center (r=0) after 30 hours of drying at different temperatures

In Figure 3, is observed a steady decrease of the temperature with cake height. For all cases the curve slope is similar, considering steady-state conditions for cake heating.

Figure 4 shows numerical results of liquid phase ratio variation versus cake height (z-coordinate) after 30 hours of drying at different heating temperatures (T_h).
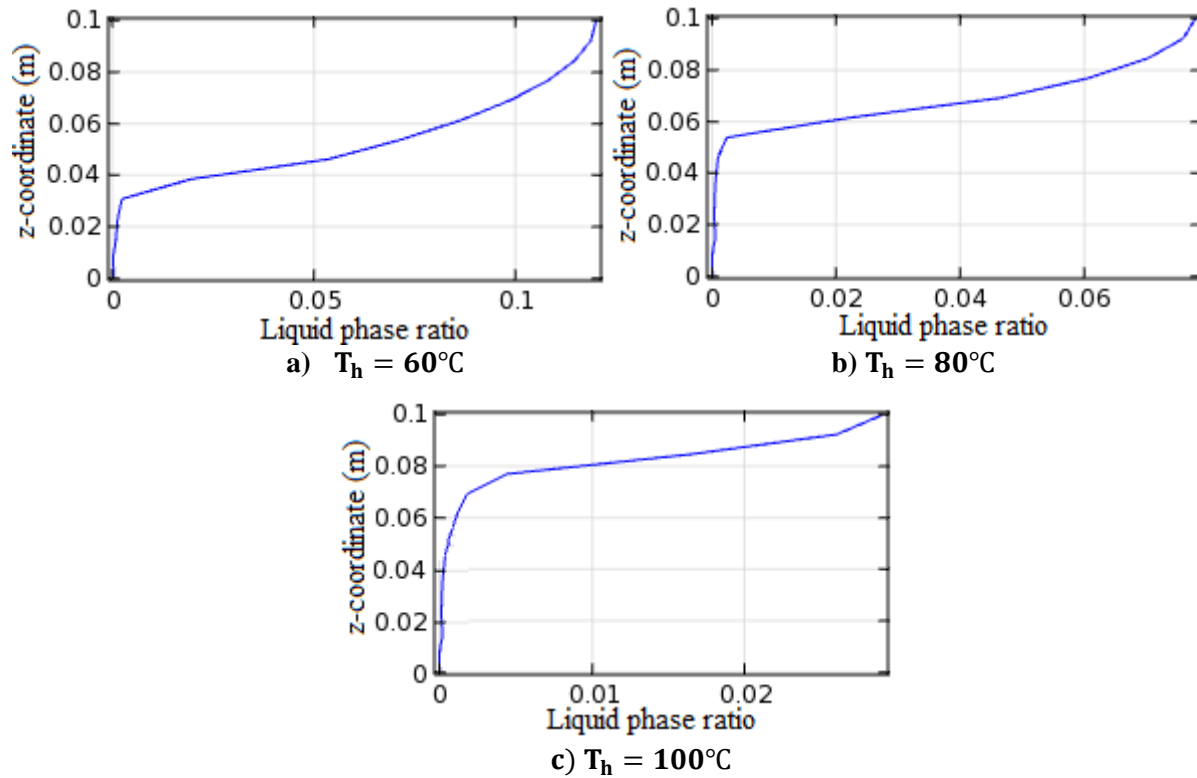

Figure 4. Variation of liquid phase ratio in sludge cake center (r=0) after 30 hours of drying at different temperatures

As cake is heated from bottom and side walls of the vacuum-filter, the liquid phase evaporation is expected to begin from cake bottom. So, analyzing the variations from Figure 4 a-c it can be observed that elimination of liquid phase is intense at cake bottom (z=0) where its value tends to zero, corresponding to complete evaporation of the water during drying process. As drying temperature is higher, dry cake height increase, as it can be identified in Figures 4, a, b and c, namely: 3 cm, 5 cm and 7 cm, respectively.

Also, the maximum value of liquid phase ratio was estimated at coordinate point z=0,1m and r=0 depending on heating temperature, as follows: 12.01 % (Figure 4,a), 7.79% (Figure 4,b) and 2.91% (Figure 4,c). So, heating temperature influence is clearly observed as initial liquid phase ratio was the same for all three cases. As initial moisture content was established at 20% (which depend on wet and dry cake masses by: $w_{L0} = (m_{wet} - m_{dry})/m_{wet}$), the initial liquid phase ratio may be estimated with relation [8], [9]:

$$\theta_{L0} = \theta_s \cdot \frac{\rho_S}{\rho_L} \cdot \frac{w_{L0}}{1-w_{L0}} \tag{1}$$

resulting: $\theta_{L0} = 0.7 \cdot \frac{1400}{1000} \cdot \frac{0.2}{1-0.2} = 0.245$, where $\theta_s = 0.7$ is the solid phase ratio, ρ_S and ρ_L are the solid and liquid phase densities with values given above.

In Figure 5 is given numerical results of gaseous phase ratio variation versus cake height (z-coordinate) after 30 hours of drying at different heating temperatures (T_h). As gaseous phase replaces the liquid one as the evaporation front moves toward cake surface during drying process, bigger value

(about 30%) are estimated at the bottom of the sludge cake, while at the top (where the cake is wet) the gaseous fraction tends to zero. Initial value of gaseous phase ratio may also be estimated, before drying process commence, considering that the ratios sum of the three phases comprises in sludge cake equals unity [8], [9]:

$$\theta_G = 1 - (\theta_{L0} + \theta_S) \qquad (2)$$

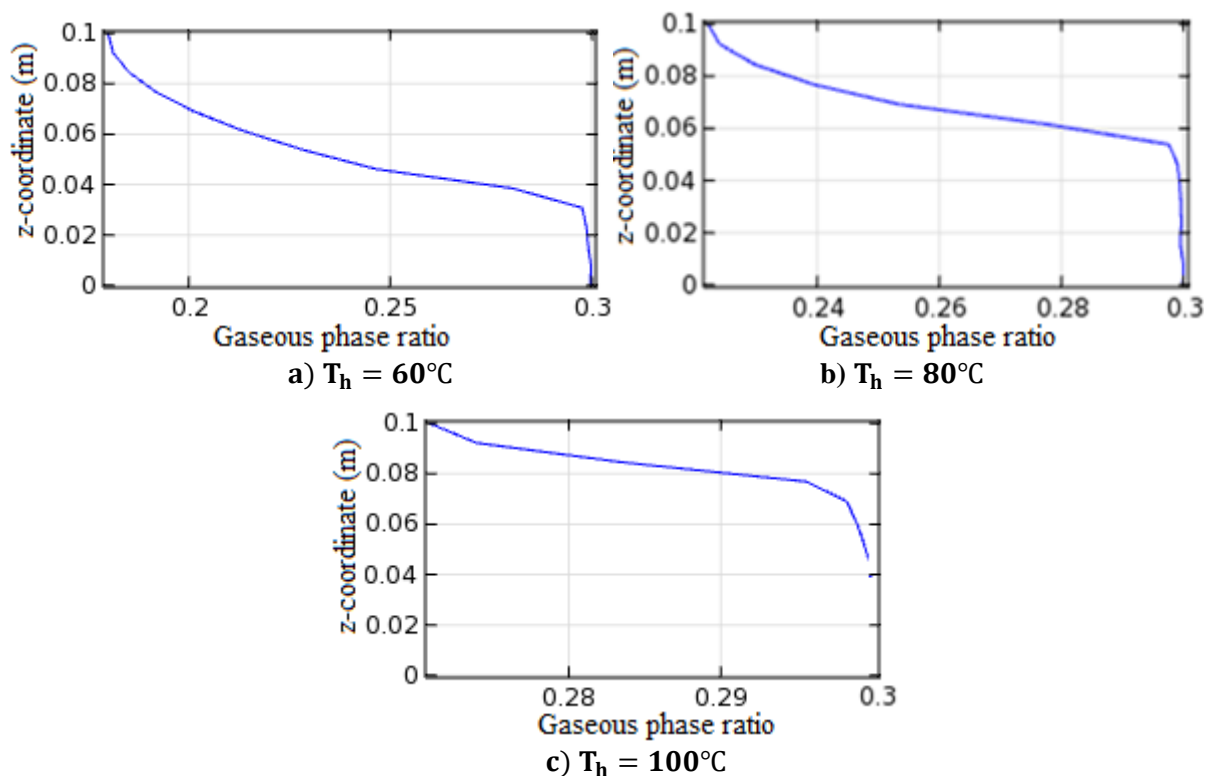resulting: $\theta_G = 1 - (0.245 + 0.7) = 0.055$ (5.5%).

Figure 5. Variation of the gaseous phase ratio in sludge cake center (r=0) after 30 hours of drying at different temperatures

So, for all heating temperatures is estimated an increase of gaseous fraction value with decreasing of sludge cake height, corresponding to sludge cake dehydration process (Figure 5,a-c).

3. Conclusions
Using finite element analysis was estimated the variation of temperature, liquid phase ratio and gaseous phase ratio of a sludge cake during drying in a vacuum filter. The study was done in function of three heating temperatures considering the cake initial moisture content of 20%. The obtained results can be useful in determining the optimum drying conditions, as well as for sizing of this type of filter [8].

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