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Numerical modeling of simultaneous heat and moisture transfer during sewage sludge drying in solar dryer

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Abstract

Mathematical modelling of the drying process enables predicting results of adopted process parameters, providing information on the course of drying in different conditions. Obtained information may be used as a basis for optimisation of the design and operating regime of such a system. The paper presents essential assumptions of the created mathematical model of a solar sewage sludge drying system and its implementation in Ansys Fluent environment. Special attention was paid to the solutions of equation of mass and heat transfer in the dried matter – the sewage sludge. The proposed solution uses additionally defined scalar parameters, i.e. sludge temperature and moisture content. The paper also presents a method for taking into account cyclic sludge shuffling. Operation of the shuffling device mechanically interferes with the layer of dried sludge and thus considerably disturbs heat and mass transfer processes in the material. Developed model was subsequently used for analysing influence of selected design and operating parameters on efficiency of the facility. The paper gives exemplary results of simulations aimed at determining impact of shuffling frequency and elevation of air blower on the drying facility's efficiency.

Keywords: sludge drying, CFD, solar drying, heat exchange, mass transfer.

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1. Introduction

Sludge processing, is a significant cost factor of a sewage treatment plant. Because of the specific physical and chemical structure of the sludge, even after the mechanical dewatering it still contains more than 70% of water by weight. Its handling on this stage causes multiple problems (transport, storage). Solar dryers seem to be the simplest and the cheapest in operation technology for reducing sludge weight. Solar sewage sludge drying facilities represent a greenhouse (chamber) type, without separated solar energy collector system. All existing solar sludge driers have

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similar design. A greenhouse structure with transparent roof is installed over a paved yard. Sewage sludge is spread over the paved floor surface. Solar radiation reaches the dried matter layer directly, passing through the transparent roof, and delivers heat required to evaporate residual humidity. Water removed from the surface of the dried sludge is removed from the facility by the flow of ventilation air [1, 2, 3, 4].

Nomenclature

a, b	constants in the equation
D_0	constant equation
D_S	diffusion coefficient of water in sludge [m^2/s]
m	mass flux density of water vapour [kg/m^2s]
T	temperature [K]
u	velocity [m/s]
X	water content in the sludge [kg water/kg dry matter]
λ_o	thermal conductivity of sludge [W/m^2K]
ρ	density [kg/m^3]
ρ_o	density of sludge [kg/m^3]
ρ_p	density of the air contained in the sewage sludge sub-area [kg/m^3]
ρ_{so}	content of sludge dry mass in a cubic metre of dried sludge [kg d.m./m^3]
ρ_{ds}	dry sludge mass density, assumed at 1100 [kg/m^3]
φ	scalar parameter (temperature, sludge moisture content)
Γ	diffusion coefficient for given scalar parameter
k	index of the scalar parameter

One of the first sewage sludge solar dryer in Poland was a pilot plant in Skarżysko-Kamienna. Their design include a light steel structure settled on a plate of impervious concrete and covered with polycarbonate plates. Inside the facility a ventilation system and installation for sludge shuffling was installed. The ventilation system was designed to provide uniform air distribution over the surface of dried sludge through the number of nozzles [1, 5].

Designing the drying processes in which the surface of a dried body contacts with the drying gas blown from a nozzle is very difficult. This is because of the fact that conditions of heat and mass transfer between the humid surface and blown gas vary depending on the distance from the nozzle axis. Additional difficulty is introduced by the heat flux resulting from solar radiation. The article presents the main assumptions and equations of the mathematical model for solar sludge drying process. With the aim of solving the discussed model a commercial software has been used, Ansys Fluent programme, with implemented author's code UDF. The application of UDF function has permitted to integrate kinetics of the process of drying the sewage sludge in Ist and IInd period of drying, and to take into consideration the conjugate nature of the exchange of heat and mass during the drying. The modelled object was an experimental solar waste-water sludge drying installation located in Skarżysko Kamienna, Poland. The modeling results have provided information to formulate guidelines for the design and operation of solar drying of sewage sludge. The article presents the conclusions both in relation to the ventilation system and installation for sludge shuffling (mixing).

2. Mathematical modeling

Key assumptions for the mathematical model describing solar sludge drying process and its digital implementation with CFD Fluent methods were presented in [1, 6, 7]. The proposed model includes heat and mass transport within dried matter (sludge), in the ambient air and on the border of both media.

Published sources concerning subject of this discussion include e.g. publications where the sludge drying facility is treated as a "black box" [8, 9]. Their authors attempt to describe the water evaporation rates using a model based on neural networks. There is also another publication [10], which presents modelling of a process system consisting of heat pumps, heat exchangers, and a solar sludge drying facility as one of the components. During recent years a few more publications describing application of CFD methods for simulating processes occurring in a solar sludge drying facility have been published, e.g. [11].

2.1. Mass and heat transport in the air

To model the process of heat and mass transfer in the air around the dried matter it is necessary to solve fluid mechanics equations for turbulent flow – continuity equation, momentum equation and substance transport equation. Those equations involve physical and chemical parameters of the described fluid. In the discussed problem this fluid is humid air treated as a mixture of oxygen, nitrogen and water vapour.

2.2. Mass transport in the dried matter

The unsteady diffusion equation was used to calculate water diffusion rate in the dried matter. To find the diffusion coefficient of the water in the sludge according to their temperature and water content, we used equation [12]:

$$D(X,T) = D_0 \cdot X^a \exp\left(-\frac{b}{T}\right) \tag{1}$$

2.3. Heat transport in the dried matter

Heat transport in the dried matter is determined by the Fourier’s law. Thermodynamic properties of the dried sludge at different temperatures and water content required by this approach (specific heat and heat conductivity) can be obtained thanks to the studies [13] and [14].

3. Model digital implementation with CFD Fluent

3.1. Geometry of the computational area

Due to the fact that solving CFD models requires high computing power, the geometry of the modelled object should be simplified as far as practicable. It may be assumed with reasonable accuracy that the modelled drying facility consists of a number of identical elements (modules) – from the thermal hydraulics point of view. A single module is understood as an area around a single blower (fan), including neighbouring sludge surface.

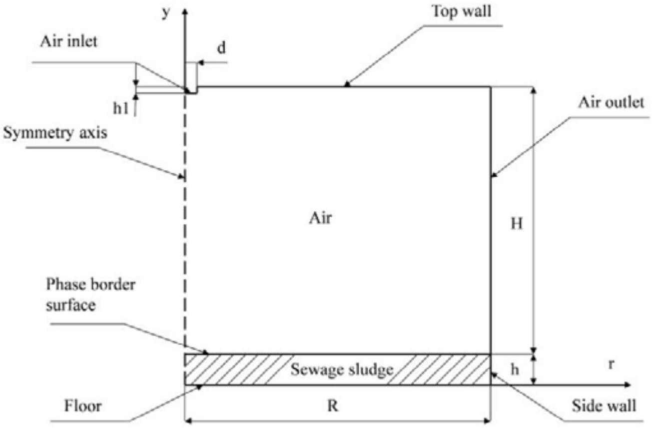

Fig. 1. Geometry of the modelled area used in calculations.

Bearing that in mind it has been decided to model only a part of the drying facility's volume in the neighbourhood of a single ventilation grate (single fan). The proposed model is two-dimensional. The modelled object is assumed to be axisymmetrical, the axis protruding from the centre of the blower, perpendicular to the sludge surface (Fig. 1).

This approach considerably accelerates computational process, allowing to investigate higher number of cases, while maintaining unchanged accuracy level. The assumed geometry of computational area is presented in the Fig. 1, and its dimensions are given in the Table 1. Geometrical parameters of the modelled area correspond with the research facility constructed at a sewage treatment plant in the City of Skarżysko-Kamienna. At this facility ventilation air inlets are located 3.2 m above the floor, with linear spacing 6 m [5]. The assumed computational area was divided into two zones: "air" and "sewage sludge" separated with a "phase border surface".

Table 1. Dimensions of the computational geometry used in calculations.

Dimensions	Value (mm)
R	3000
H	2920 – 3120
h	100 – 300
d	240
h1	20

3.2. Modelling air-sludge border

The Fluent CFD package does not provide standardised boundary condition type which would enable defining simultaneous mass and heat transfer processes occurring at a physical border between the solid (sludge) and gaseous (humid air) phases. In order to implement appropriate conditions it is required to incorporate appropriate procedures in form of so-called User-Defined Functions (UDF). In order to implement the discussed conditions at the border between solid and gaseous phases, a following sequence of actions accomplished by five UDFs was assumed:

- Mass fraction of water vapour in the air adjacent to the dried matter surface is calculated from the temperature of the heated matter surface.
- Diffusion coefficient for the water vapour in entire "air" zone is determined according to the air temperature at its assumed pressure (UDF 2) [15].
- Then mass flow of water which leaves the surface of the dried matter is determined.
- UDF 4 is used to determine the heat flux reaching the dried matter surface ("wall" type boundary, belonging to the "sewage sludge" zone), which is driven by convection, solar radiation, heat of evaporation.
- UDF 5 assigns sludge surface temperature to the adjacent air.

3.3. Implementation of sludge shuffling

Discussed model of solar sewage sludge drying process includes heat and mass transfer within the air and sewage layer. While defining material properties for both sub-areas, it would be natural to determine the sludge sub-area as a solid with defined parameters such as: density, heat conductivity, specific heat capacity etc. However, Fluent software is unable to resolve the mass transfer equation within an area defined as solid. Therefore, in order to obtain the solution of the solar sludge drying process, the sludge sub-area was defined as a fluid with the composition and physical properties identical as those for the air sub-area. In order to implement the heat and mass transfer equations within the sludge sub-area, additional conservation equations were later defined using so-called User-Defined Scalars (UDS). Those additional scalars whose transfer is modelled are sludge temperature and moisture content. Fluent resolves following scalar value transfer equation [18]:

$$\frac{\partial \rho \phi_k}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho \cdot u_i \cdot \phi_k - \Gamma_k \frac{\partial \phi_k}{\partial x_i} \right) = S_{\varphi k} \tag{2}$$

After removing internal sources and the convective component (which does not exist for the discussed case), the equation of scalar value transfer is simplified to:

$$\frac{\partial \rho \phi_k}{\partial t} = \frac{\partial}{\partial x_i}\left(\Gamma_k \frac{\partial \phi_k}{\partial x_i} \right) \tag{3}$$

Assigning to the sludge sub-area material properties same as those of the air sub-area (especially in case of density) requires carrying out certain conversions when determining diffusion coefficients and boundary conditions for heat and mass transfer equations. Basing on (3), the equation of mass transfer within a solid may be expressed as:

$$\frac{\partial \rho_p X}{\partial t} = \frac{\partial}{\partial x_i}\left(\Gamma_X \cdot \frac{\partial X}{\partial x_i} \right) \tag{4}$$

For the equation (4), the diffusion coefficient Γ_X is a product of density of material for which the equation is being resolved (air) and the actual diffusion coefficient of moisture within the sludge D_s:

$$\Gamma_X = \rho_p \cdot D_s \tag{5}$$

Fluent permits defining two types of boundary conditions for scalar value transfer equations: distribution at the boundary and flux across the boundary – defined as a product of the gradient on the direction normal to the boundary and diffusion coefficient. The model of solar sludge drying uses a flux type boundary condition at the air-sludge interface (phase boundary). For the described conditions of the problem, this condition has a form:

$$\Gamma_X \cdot \frac{\partial X}{\partial n} = \frac{\dot{m}}{\dfrac{\rho_{So}}{\rho_{p\cdot}}} \tag{6}$$

Flux of water ($\dot{m}$) removed from dried matter is determined by UDF 3. Modelling mass transfer within the dried matter (using equation 4) based on using material moisture content defined as a mass ratio of the moisture contained in the matter to the dried mass – X, leads to a necessity of defining flux of water transferred by diffusion (equation 6) by taking into account concentration of the dry matter within the humid material [16, 17]. For the needs of this study, dry matter content in a 1 m^3 of dried matter was expressed using following relation:

$$\rho_{s0} = \frac{1000 \cdot \rho_{ds}}{X_0 \cdot \rho_{ds} + 1000} \tag{7}$$

In the developed model, this value is calculated at the beginning of each simulation run for the initial moisture content of X_0. Then it remains constant until the end of the run. Sludge density is determined according to the current moisture content and dry matter content in 1 m^3 of the dried sludge at the zero time (equation 8).

$$\rho_o = \rho_{s0} + X \cdot \rho_{s0} \tag{8}$$

Analogically to the mass transfer equation, discussion of the heat transfer within the dried matter leads to:

$$\frac{\partial \rho_p T}{\partial t} = \frac{\partial}{\partial x_i}\left(\Gamma_T \cdot \frac{\partial T}{\partial x_i}\right) \tag{9}$$

Diffusion coefficient for the equation (9) is a ratio of sludge thermal conductivity (λ_o) and its specific heat capacity (c_o) multiplied by the ratio of sludge density to air density:

$$\Gamma_T = \frac{\lambda_o}{c_o \cdot \dfrac{\rho_o}{\rho_p}} \tag{10}$$

Also at the interface between the air and sludge (phase boundary) a flux type condition is used. For the conditions of the investigated problem it takes the following form:

$$\Gamma_T \cdot \frac{\partial T}{\partial n} = \frac{q}{c_o \cdot \dfrac{\rho_o}{\rho_{p\cdot}}} \tag{11}$$

Heat flux (q) which reaches sludge surface on the air side is calculated by UDF 4. Presented methodology allows effectively implementing equations of heat and mass transfer within the sludge sub-area.

During the experimental tests at Skarżysko-Kamienna facility, the sludge shuffling device worked automatically, carrying out 12 runs per day. Operation of the shuffling device by mechanically interfering with the sludge layer introduces considerable distortions into the heat and mass transfer processes within the dried matter. This is because after each shuffling run the sludge parameters are uniformised within the whole volume of the layer; this especially applies to the temperature and moisture content. In order to implement the shuffling in the discussed model, following algorithm was adopted:

- parameters of the dried matter – moisture content and temperature – are averaged across the whole sludge sub-area with the pre-set frequency, matching the shuffling frequency (every 2 hours);
- averaged moisture content and temperature parameters are assigned to the sludge sub-area as initial conditions for further part of the simulation run (until the next shuffling, when the parameters get averaged again).

4. Results and discussion

The paper presents some exemplary results of simulations based on the discussed model, carried out to determine impact of shuffling frequency and air blower elevation on facility's efficiency.

4.1. Impact of sludge shuffling frequency on drying rates

The shuffling schedule of the Skarżysko-Kamienna facility assumed operation of the shuffling device at a steady linear speed of 0.5 m/min. The total duration of a single shuffling run was 120 min. Because upon completing a run, the shuffling device would reverse its direction and restart its movement, the actual shuffling intervals at different areas of the layer varied. Only the sludge located in the central part of the facility were shuffled at equal 120 min intervals. The section below presents simulation results for two different shuffling intervals, corresponding to the point 10 metres from the end of a shuffling device's track, and in the centre of the track. The simulation was made for a single day of summer. No significant impact of shuffling frequency on average daily drying rate has been identified: shuffling every 120 minutes – 8.12 kg water/m^{2}d; shuffling at intervals of 200 minutes and 40 minutes –

8.1 kg water/m^{2}d. However, momentary and local values of this parameter may differ considerably for different shuffling frequencies. Sludge shuffling on one hand increases moisture content at the layer surface, but on the other it lowers its temperature (during day). Condition for the hour 13:30 for both shuffling frequencies is compared below. If the sludge is not shuffled at 13:00 (shuffling at 200/40 min intervals), the sludge is locally overdried around the blower axis, which causes transfer into the II drying period and reduction of drying rate (Fig. 2).

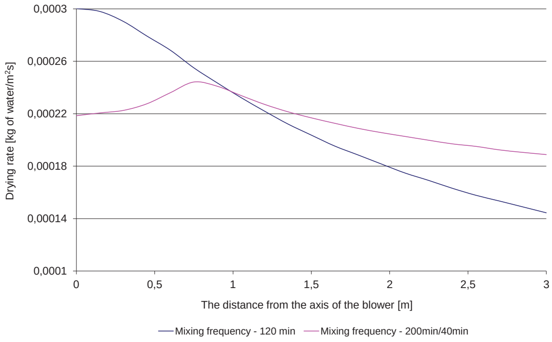

Fig. 2. Sludge drying rate as a function of distance from the blower axis for different shuffling frequencies. Situation at 13:30 (simulation result).

However, at the given time, this area is a circle with a radius of approximately 1 m. And if the sludge is not cooled by shuffling at 13:00 (as it happens in case of shuffling every 120 min), higher drying rate is observed on entire remaining part of the layer, with much larger surface area (Fig. 2).

4.2. Impact of blower elevation on drying rate

The section below presents results of simulating impact of blower elevation on sludge drying rate. Just like in previous case, the calculations were performed for weather conditions of a single summer day. Three values of elevation (above the facility floor) were modelled: 1) H+h=2700 mm; 2) H+h=3200 mm; 3) H+h=3700 mm;

The modelling has demonstrated that change of blower elevation above the humid surface in the discussed case does not have significant impact on the average drying rate (Fig. 3a). Certain small differences are only observed during daylight hours. Calculated average specific (per square metre) sludge drying rate was: 8.21 kg water/m^{2}d for H+h=2700 mm; 8.12 kg water/m^{2}d for H+h=3200 mm; 8.03 kg water/m^{2}d for H+h=3700 mm. Therefore lowering the blower by 1 m led to increase of the average drying rate by only 0.18 kg water/m^{2}d. Nevertheless, the simulation results reveal that local drying rates may considerably differ for different blower elevations (Fig. 3b).

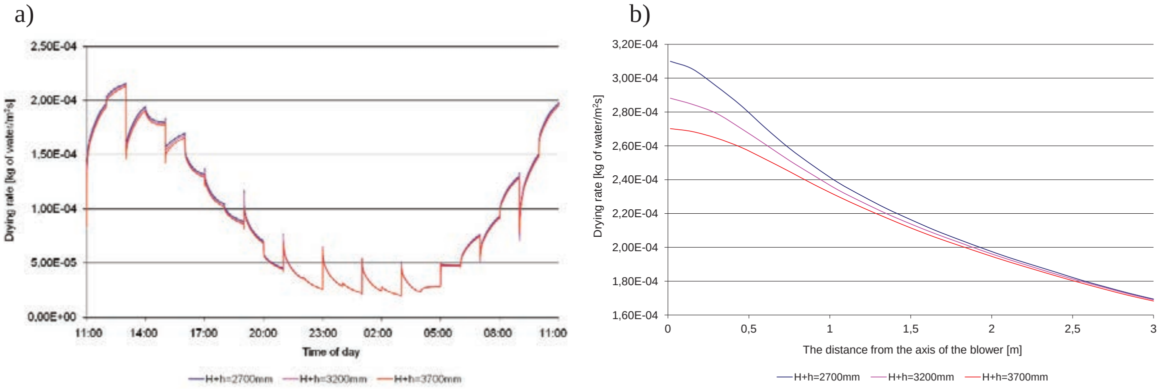

Fig. 3. (a) Comparison of daily variations of average drying rate (for the whole layer surface) for different blower elevations (simulation result); (b) Sludge drying rate as a function of distance from the blower axis for different blower elevation values for 12:00 hours – one hour after shuffling (simulation results).

The largest differences are observed close to the blower axis, i.e. in the active drying area. Further away from the blower axis, in the passive drying area, the differences disappear. The highest drying rate is observed for the lowest blower elevation.

5. Conclusions

Solar drying facilities dedicated to sewage sludge remain a novelty. Their specificity – high dependence of operating parameters on local weather conditions – considerably complicates optimising system configuration and operating parameters for different sites, seasons, sludge moisture contents etc.

Basing on the simulation results presented in the paper it may be concluded that the sludge shuffling frequency should be planned in such a way that the layer is shuffled only after the drying rate drops below a certain level, and not at intervals which prevent local overdrying. Such a way of working would on one hand enable saving electricity (thanks to the reduced operating time of the shuffling device) and on the other increase the drying rate. However, increasing intervals between the shuffling cycles in comparison to the schedule used at Skarżysko-Kamienna facility, would require increasing travelling speed of the shuffling device, so the areas located near the ends of the device's track would not be shuffled too rarely. Moreover, performed simulations demonstrate that the blower elevation does not have significant impact on the averages specific drying rate. Nevertheless there are differences in the distribution of local drying rate as a function of distance from the blower axis. Lower elevation of the blower above the humid surface leads to a higher drying rate in the active drying area, with all relevant consequences.

Therefore, when changing the blower elevation it needs to be remembered to change sludge shuffling frequency too, in order to prevent local overdrying.

References

[1] Krawczyk P., 2008. Research of the heat – flow processes in sewage sludge solar dryer (in Polish). PhD dissertation, Division of Power Machines and Devices, Institute of Heat Engineering, Warsaw University of Technology,

[2] Luboschik U., 1999, Solar sludge drying – based on IST process, Renowable Energy 16, 785-788

[3] Bennamoun L., 2012, Solar drying of wastewater sludge: A review, Renewable and Sustainable Energy Reviews 16, 1061– 1073

[4] Salihoglu N., K., and Pinarli V., and Salihoglu G., 2007, Solar drying in sludge management in Turkey, Renewable Energy 32, 1661–1675

[5] Szczygieł J., and Szwarc W., and Krawczyk P., 2005, Technologia słonecznego suszenia osadów ściekowych (The technology of solar drying of sewage sludge), Czysta energia, pp. 36-37 (in Polish)

[6] Badyda K., and Krawczyk P., 2008, Research of heat and flow processes in a solar waste–water sludge dryer. Polish Journal of Environmental Studies vol. 17, No. 3A, pp. 28 – 32

[7] Krawczyk P., and Badyda K., 2011, Two-dimensional CFD modeling of the heat and mass transfer process during sewage sludge drying in a solar dryer. Archives of thermodynamics Vol. 32(2011), No. 4, pp. 3–16

[8] Seginer I., and Bux M., 2005, Prediction of Evaporation Rate in a Solar Dryer for Sewage Sludge. Agricultural Engineering International: the CIGR Ejournal. Manuscript EE 05 009. Vol. VII.

[9] Seginer I., and Bux M., 2006, Modeling Solar Drying Rate of Wastewater Sludge, Drying Technology, 24:11, pp. 1353-1363,

[10] Slim R., and Zoughaib A., and Clodic D., 2008, Modeling of a solar and heat pump sludge drying system. International Journal of Refrigeration 31, pp. 1156 – 1168.

[11] Putranto A., and Chena X., D., 2014, A simple and effective model for modeling of convective drying of sewage sludge: the reaction engineering approach (REA). Procedia Chemistry 9, pp. 77 – 87.

[12] Stolarek P., and Ledakowicz S., and Pakowski Z., Grębowski M., 2003, Determination of diffusivity of water in the sludge by means of thermogravimetry (in Polish). Materiały konferencyjne „X Sympozjum Suszarnictwa". Łódź, 17 – 19 september 2003 r.

[13] Arlabosse P., Chavez S., Prevot C. Drying of municipal sewage sludge: from a laboratory scale batch indirect dryer to the paddle dryer. Brazilian Journal of Chemical Engineering Vol. 22, No. 02, pp. 227 - 232, April - June, 2005

[14] Dewil R.,Baeyens J., Neyens E. Fenton peroxidation improves the drying performance of waste activated sludge. Journal of Hazardous Materials B117 (2005) 161–170

[15] Strumiłło Cz., 1983, Fundamentals of theory and techniques of drying (in Polish). Warsaw, WNT

[16] Trujillo F. J, and Wiangkaew Ch., and Pham Q. T., 2007, Drying modeling and water diffusivity in beef meat. Journal of Food Engineering 78, 74–85.

[17] Catalano P., and Fucci F., and Giametta F., and La Fianza G., 2008, A System for Food Drying Using Humidity Control and Low Temperature. Agricultural Engineering International: the CIGR Ejournal. Manuscript Manuscript FP 07 012. Vol. X.

[18] Fluent Incorporated, „FLUENT User's Guide", www.fluent.com.