The relative change of drying rate as a function of the cumulative ventilation air drying potential in a thin-layer solar drying facility

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Abstract. Controlling low-temperature drying facilities which utilise non-prepared air is quite difficult, due to very large variability of ventilation air parameters – both in daily and seasonal cycles. The results of experimental studies of sewage sludge solar drying process in thin-layer solar dryer have been presented. It was found that regardless of weather conditions, the rate of sewage sludge drying is significantly changed during drying process. The results showed that the rate of drying decreases with increasing so called cumulative ventilation air drying potential. Knowledge on current drying rate provides new possibilities for controlling such systems. Based on the results, operating recommendations for analysed type of dryer have been formulated.
Experimental data analysed in the paper was collected in 2012 - 2014 during operation of a test solar drying facility in a sewage treatment plant in Błonie near Warsaw, Poland.

Keywords: solar drying, sewage sludge, drying rate calculation, thin-layer solar dryer

1. Introduction
An inseparable element of wastewater treatment is sewage sludge created in this process. This waste is highly hydrated and it is a mixture of various living and dead microorganisms as well as organic and mineral components [1]. Its management causes major problems for the operators of sewage treatment plants. Rules of law in this range prefer thermal methods of waste transformation relative to other methods of their management, i.e. storage or reuse for natural purposes [2], [3], [4], [5], [6]. Dryers are elements that allow to transform sewage sludge from a hydrated form, which contain about 80% of water to a form enabling using it as a fuel (about 20% of water). A reasonable solution for small and medium-sized sewage treatment plants seems to be solar dryers [7], [8], [9]. Despite their increasing popularity, there are only few publications describing the thermal-flow processes taking place in this type of facilities. There is also a lack of design and operational recommendations concerning the construction of sludge solar dryers. In the article, there are presented the results of research regarding a new type of thin-layer solar dryer.

2. Pilot plant
Research on the process of sewage sludge solar drying was carried out in an experimental thin-layer solar dryer built in the sewage treatment plant in Błonie near Warsaw, Poland. The basic design assumptions of the dryer were presented in [10], [11]. In the test dryer, a bed of dried sludge was laid on a horizontal band conveyor placed in a tunnel roofed by a transparent material for solar radiation (Fig.1).
Figure 1. The experimental thin-layer solar drying facility of sewage sludge in Blonie (Poland).

The band conveyor is used to transport dried sludge inside the tunnel (drying chamber). The air flow inside the drying chamber was forced by mechanical ventilation (4 exhaust fans with rate of delivery each about 6'000 m³/h). The sludge during the feeding was subjected to the forming process by a spreader. The diameter of formed bed elements during the tests was 12-15 mm (Fig.2). The drying facility has a length of 30 m and a width of 3 m.

Figure 2. The bed of dried sewage sludge in experimental thin-layer solar drying facility

The research program included continuous acquisition:
- temperature and relative humidity of the supply air to the drying facility and leaving the drying facility;
- the mass of sediments remaining on the separated area of the belt by a weighbridge installed under the drying belt;
- content of dry matter and humidity of dried sludge - samples analyzed in the treatment plant laboratory.

The temperature and relative humidity of the air were recorded with a time base of 5 minutes. The results of the measurements were used to analyze the nature of changes in the drying rate of sludge.
3. Method of measurement parameters’ analysis

In the articles [12], [13] the concept of the drying potential of the ventilation air was implemented. It is defined as the theoretical value of the driving force of the drying process (difference between the moisture content in the air having contact with moist material and in the free flow), which occurs in the first drying period with a ventilation air of known temperature and relative humidity.

The rate of moisture evaporation from the dried material can be expressed using the equation [14], [15]:

\[ W = A \cdot k_y \cdot (Y_s - Y) \]  \hspace{1cm} (1)

The moisture content \( Y_s \) corresponds to the moisture content in the saturation state at the temperature of the liquid film covering the dried material \( t_s \) and it depends on the value of this temperature. The driving force of the moisture evaporation process is the difference between the moisture content in the air having contact with the dried material \( Y_s \) and the moisture content in the main flow \( Y \). Based on equation (1), this value can be expressed as:

\[ \frac{W}{A \cdot k_y} = (Y_s - Y) \]  \hspace{1cm} (2)

The mass exchange coefficient \( k_y \) depends mainly on the hydrodynamic conditions of the process [16]. The thickness of the boundary layer for mass transfer, which determines the \( k_y \) coefficient, depends on the velocity of the gas above the surface of the dried body according to the dependence: \( k_y \approx U^{0.8} \) [17].

Considering a drying facility with a known active surface of a bed of dried material and invariable settings of the ventilation, during the process, it can be assumed that:

\[ A \cdot k_y = C = const. \]  \hspace{1cm} (3)

In this case, the drying rate depends only on the driving force of the drying process:

\[ W = C \cdot (Y_s - Y) \]  \hspace{1cm} (4)

According to the theory of drying in the area of constant drying rate (first drying period), the temperature of the material surface in contact with air is constant and is equal to the temperature of the wet thermometer determined for the parameters of the ventilation air [18]. Being in accordance with the theory of drying, it is feasible to determine the surface temperature of the dried material \( t_s = t_m \left(t_{zm}, \phi_z\right) \), thus the moisture content in the air in contact with the dried material \( Y_s \), only on the basis of knowledge of the temperature and humidity of the ventilation air. Therefore, it is possible to determine the theoretical value of the driving force of the drying process, which occurs under the conditions of the first drying period using ventilation air of known temperature and relative humidity. This quantity for the purpose of this work has been defined as the drying potential of the ventilation air \( P_z \):

\[ P_z = Y_m(t_{zm}, \phi = 100\%) - Y_z \]  \hspace{1cm} (5)

where: \( P_z \) – drying potential of the ventilation air, \( Y_m \) – moisture content in the temperature of the wet thermometer \( t_m \) and in the saturation state \( \phi =100\% \), \( Y_z \) – moisture content in the ventilation air (external).

Having the temperature \( t_z \) and the relative humidity \( \phi_z \) of the ventilation air, it is possible to determine the value of the moisture absorption potential \( P_z \) for this air.

It follows from considerations that the instantaneous drying rate should be proportional to the instantaneous value of moisture removal potential of ventilation air.

\[ W = C \cdot (Y_m - Y_z) = C \cdot P_z \]  \hspace{1cm} (6)

The influence of energy supplied to the drying facility by direct solar radiation on the rate of drying of sludge, except the short-term periods of the largest solar activity, is low (isenthalpic process) [11].

During the drying, the parameters of the ventilation air change continuously. Integral over time of drying potential of the ventilation air was called the cumulative potential of the ventilation air \( S \) [12] - equation 7.
It is a quantity directly proportional to the amount of evaporated water in a given drying cycle from its beginning until the time of t.

The collected experimental data (over 20 drying cycles) from the research installation was analyzed for the drying rate as a function of ventilation air potential for different values of cumulative potential. Consideration of the drying rate as a function of drying potential of the ventilation air allows the analysis results to be independent from the continuously changing atmospheric conditions.

4. Results and discussion

For each of the analyzed drying cycles, the values of the drying potential and the cumulative ventilation air drying potential were determined. The drying rate can be expressed as the product of water gain content in the ventilation air and the flow rate of this air. Because during the research, the air flow was constant in further analyzes only the values related to the air mass unit were used. The results of the drying process are shown in Figures 3 and 4. The collected measurement data were divided into four groups depending on the value of the cumulative ventilation air drying potential. For each group, the average proportionality coefficient was determined between the ventilation air drying potential and the drying rate expressed by increasing the moisture content in the ventilation air. It turned out that the mentioned dependence changes substantially with the drying process, i.e. the gain the cumulative potential value. The higher value of cumulative potential causes the lower drying rate under the same atmospheric conditions, i.e. with the same ventilation air drying potential (table 1).

Table 1. The average coefficient of proportionality between the drying potential of ventilation air and the rate of drying for different values of cumulative potential S

| Cumulative potential S, (kgsteam*s/kgair) | The average coefficient of proportionality between the drying potential of ventilation air and the rate of drying |
|-----------------------------------------|--------------------------------------------------|
| 0-100                                   | 0.2875                                           |
| 100-200                                 | 0.2207                                           |
| 200-300                                 | 0.1753                                           |
| 300-400                                 | 0.0931                                           |
Figure 4. Increase of moisture content in the ventilation air as a function of drying potential for that air – experimental data (♦ – cumulative ventilation air drying potential in a range 200-300, ■ – cumulative ventilation air drying potential in a range 300 - 400)

At the same time, it is clear that for the analyzed drying cycles, the average sludge humidity remained higher than the critical humidity at which occurs transition from the not bound water area to the bound water area and was minimum about 2 kg\textsubscript{water}/kg\textsubscript{dry matter} [12]. As research show [16], [19], [20], the critical humidity for sewage sludge is approx. 0.3 kg\textsubscript{water}/kg\textsubscript{dry matter}. According to the author, it is caused by the lack of moving the bed of dried material during the drying process and the drying of its top layer. This, in turn, hinders the diffusion of water from the interior of the dried material to the surface of contact with air. Consequently, it causes a reduction of the average drying rate in relation to realisable under the given conditions.

5. Conclusions and summary

In a large thickness of the dried material bed (about 20-30 cm) solar dryers, mixer supports the transport of moisture from the interior of the sludge to the contact surface with the drying air. In the presented solution of thin-layer drying facility, the similar component is missing. In the design assumptions, the bed was supposed to be such a small thickness that the moisture could effectively diffuse from the interior of the dried material to the contact surface with the air. As the presented results show, with the progress of drying expressed by the cumulative ventilation air drying potential, the drying rate drops significantly despite the average humidity of the material remaining above the limit value for its transition to the second drying period. Therefore, it seems, that to better utilization the ventilation air drying potential, and hence to increase the efficiency of the drying facility, this kind of component, which forces the move of sludge, should be introduced into the analyzed type of installation. This effect can be achieved, for example, by dividing the drying belt and transferring the dried material from one belt to another.

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