

## Cumulative ventilation air drying potential as an indication of dry mass content in wastewater sludge 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 paper defines the concept of cumulative drying potential of ventilation air and presents experimental evidence that there is a relation between this parameter and condition of the dried matter (sewage sludge). Knowledge on current dry mass content in the dried matter (sewage sludge) provides new possibilities for controlling such systems. Experimental data analysed in the paper was collected in early 2012 during operation of a test solar drying facility in a sewage treatment plant in Błonie near Warsaw, Poland.

**Keywords:** Sewage sludge drying; Solar drying; Dry matter calculation

### Nomenclature

$A$	–	area, $m^2$
$C$	–	constant in the equation
$dm$	–	dry matter content in sewage sludge, %
$I_{dm}$	–	initial dry matter content in sewage sludge, %
$I_m$	–	initial unitary mass, $kg/m^2$
$k_y$	–	mass transfer coefficient, $kg\ water/m^2s\ Y$

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$m_w$	–	mass of evaporated water, kg
$p_{sz}$	–	water vapour pressure in the air in saturation conditions, Pa
$p_{sm}$	–	water vapour saturation pressure for wet bulb temperature, Pa
$P_z$	–	ventilation air drying potential, kg water/kg dry air
$S$	–	cumulated drying potential of ventilation air, (kg water/kg dry air) s
$t$	–	time, s
$t_m$	–	wet bulb temperature, °C
$t_s$	–	temperature of a liquid layer covering the dried matter, °C
$t_z$	–	ventilation air temperature, °C
$U$	–	velocity, m/s
$W$	–	drying rate, kg water/s
$X_{cr}$	–	critical water content in the sludge, kg water/kg dry matter
$Y$	–	moisture content in the air in the main flow, kg water/kg dry air
$Y_s$	–	moisture content in the air at a liquid layer surface, kg water/kg dry air
$Y_m$	–	moisture content in the air in saturation conditions at a wet bulb temperature, kg water/kg dry air
$Y_z$	–	moisture content in the ventilation air, kg water/kg dry air

### Greek symbols

$\phi$	–	relative humidity, %
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## 1 Introduction

Process of drying humid matter involves simultaneous transfer of heat and mass within the matter, at the phase boundary layer and within the gas flow. In a general case the process of drying is considerably affected by both external ambient conditions and internal structure of the dried matter. Those factors, to various extent, influence the rate of heat and mass transfer. During the first drying period the exchange mechanisms within the boundary layer are decisive, while during the second period additional resistance attributable to processes occurring within the dried matter appears.

Except for the hydrodynamic and thermal boundary layers, water evaporation in the direct neighbourhood of the evaporation surface (dried matter) causes a concentration (diffusion) boundary layer to form. Within this layer the molecular vapour pressure (diffusive pressure) changes from  $p_{sat}$  at the evaporation surface (saturation pressure at the temperature of a liquid layer covering the surface) to  $p$  on the outer edge of the boundary layer. Due to diffusion the evaporated liquid penetrates the surface layer of the dried matter and passes into the surrounding medium [1,2]. Humidity of the matter decreases due to continuous humidity extraction from the inner layers of the matter towards the surface and its further evaporation. When it drops

below certain critical value ( $X_{cr}$ ), the flow of humidity towards the surface of the dried matter starts to decrease. As a result the vapour pressure over the matter surface drops too, leading to decreasing drying rates.

Research [3–5] shows that critical humidity for sewage sludge, at which passage from the free water to bound water occurs, is approx. 0.3 kg H<sub>2</sub>O/kg dry mass, i.e. hydration of approximately 23%. Sewage sludge delivered to a drying facility usually has humidity of approximately 4 kg H<sub>2</sub>O/kg dry mass, i.e. hydration of ca. 80%. Typical hydration of sludge after the drying process is some 20–25%. This shows that the process of sewage sludge drying carried out in typical commercial systems is carried out exclusively under conditions of the first drying period.

## 2 Cumulative drying potential of ventilation air

Rate at which water evaporates from the dried matter may be expressed with equation [6,7]

$$W = Ak_y(Y_s - Y) . \quad (1)$$

Moisture content  $Y_s$  is equal to the moisture content in saturation conditions for the temperature of liquid layer covering the dried matter  $t_s$  and is a function of that temperature. Driving force for the water evaporation is the difference between the moisture content in the air adjacent to the dried matter  $Y_s$  and moisture content in the main flow  $Y$ . Using the Eq. (1) it is possible to express this parameter as

$$\frac{W}{Ak_y} = (Y_s - Y) . \quad (2)$$

Mass transfer coefficient  $k_y$  depends mainly on hydrodynamic conditions of the process [4]. Thickness of the surface layer for mass transfer, which determines the  $k_y$  value, depends on the linear velocity of the gas over the dried surface according to the relation  $k_y \approx U^{0.8}$  [8]. When discussing a drying facility with a known active area of the dried matter and ventilation system parameters fixed during the process ( $U = const$ ), it may be assumed that

$$Ak_y = C = const . \quad (3)$$

In such a case drying rate depends only on the driving force of the drying process

$$W = C(Y_s - Y) . \quad (4)$$

According to the drying theory, within the constant drying rate area (first drying period) the temperature of the matter surface in contact with air is constant and equal to the wet bulb temperature for ventilation air parameters [8,9]. Thus it is possible, in accordance with the drying theory, to determine surface temperature of the dried matter  $t_s = t_m(t_z, \phi)$ , and therefore also the moisture content in the air adjacent to the dried matter  $Y_s$ , basing only on knowledge of ventilation air temperature and humidity. This means that it is also possible to determine theoretical value of the driving force of the drying process which will occur under first drying period conditions, when using ventilation air of known temperature and relative humidity. Within this study this value is called the drying potential of ventilation air

$$P_z = Y_m(t_m, \phi = 100\%) - Y_z . \quad (5)$$

With known ventilation air temperature,  $t_z$ , and relative humidity,  $\phi$ , it is possible to determine the value of drying potential of that air with the following steps:

- Calculate water vapour pressure in this air in saturation conditions for known ventilation air temperature  $t_z$ . This may be done with a formula [10]

$$p_{sz} = 610.78 e^{\left(\frac{17.2693882 t_z}{t_z + 237.3}\right)} . \quad (6)$$

- Knowing vapour saturation pressure  $p_{sz}$  for the air at the temperature  $t_z$  as well as air relative humidity  $\phi$  calculate the ventilation air moisture content [9]

$$Y_z = 0.62198 \frac{\phi p_s}{101325 - \phi p_{sz}} . \quad (7)$$

- Determine the wet bulb temperature for ventilation air parameters. Literature rarely provides equations for relation between the wet bulb temperature and other parameters of the air given in explicit form. This study utilises equation proposed by Stull [11]:

$$t_m = t_z \tan(0.151977(\phi + 8.313659)^{0.5}) + \tan(t_z + \phi) - \tan(\phi - 1.676331) + 0.00391838\phi^{1.5} \tan(0.023101\phi) - 4.686035 \quad (8)$$

- Then for the obtained wet bulb temperature  $t_m$  calculate vapour saturation pressure for that temperature and, assuming air relative hu-

midity of 100%, also moisture content in that air [9,10]:

$$p_{sm} = 610.78 e^{\left(\frac{17.2693882 t_m}{t_m + 237.3}\right)}, \quad (9)$$

$$Y_m = 0.62198 \frac{p_{sm}}{101325 - p_{sm}}. \quad (10)$$

This discussion shows that a momentary drying rate should be proportional to a momentary value of drying potential of the ventilation air

$$W = C (Y_m - Y_z) = C P_z. \quad (11)$$

Ventilation air parameters vary continuously during the drying process, and so does the drying potential of the air fed into the drying facility. A diagram showing variability of air drying potential during a single drying cycle is shown in Fig. 1. Analysed value reaches its maximum around noon and drops to nearly zero in night time.

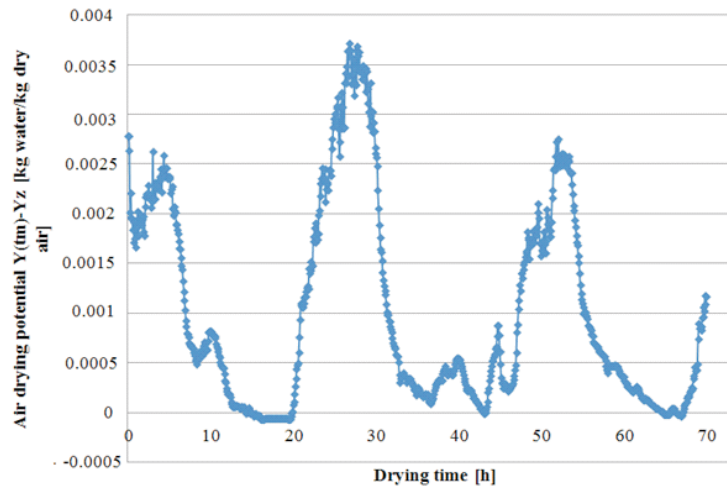


Figure 1. Variability of air drying potential during a single drying cycle.

Amount of evaporated water within a drying cycle may be determined by integrating both sides of the Eq. (11) over time. This yields

$$m_w = \int_0^t W(t)dt = C \int_0^t P_z(t)dt. \quad (12)$$

Within this study the integer of the ventilation air drying potential over time

$$S = \int_0^t P_z(t) dt . \quad (13)$$

is called cumulative ventilation air drying potential. According to the discussion this value should be directly proportional to the amount of water evaporated throughout a drying cycle, from its beginning until the time designated as  $t$

$$m_w = C S . \quad (14)$$

The discussion presented above is correct as long, as the dried sludge remains in the first drying period and the impact of energy absorbed by the dried matter from the direct solar radiation on the drying process is small [12].

### 3 Experimental research

#### 3.1 Research system

Key design assumptions for the thin-layer drying facility have been presented in [12,13]. The research system has been installed at the wastewater treatment plant in Błonie, near Warsaw. The facility is 30 m long and 3 m wide. Surface of the dried sludge layer is approx. 90 m<sup>2</sup>. The forming of the sludge about to be dried is carried out with a sieve spreader. The covering structure has been made of 10 mm thick polycarbonate panels. The test facility is divided into two parts with a barrier in the midlength. In each part the drying process may be carried out at different ventilation system settings, different layer shape, etc. The view of the test system is given in Figs. 2 and 3.

The test drying facility is equipped with a mechanical ventilation system composed of four extraction fans forcing the air flow over the dried sludge layer. The fans are installed near the centre of the drying tunnel, on both sides of the separation barrier. The air is sucked in through open ends of the tunnel. The air flow is turbulised by polycarbonate barriers installed inside the facility. This issue has been described in detail in [12,13]. Measurements of the drying process have been carried out with a system of thermohygrometers, a pyrometer, a pyranometer, and a platform scale installed below the belt.

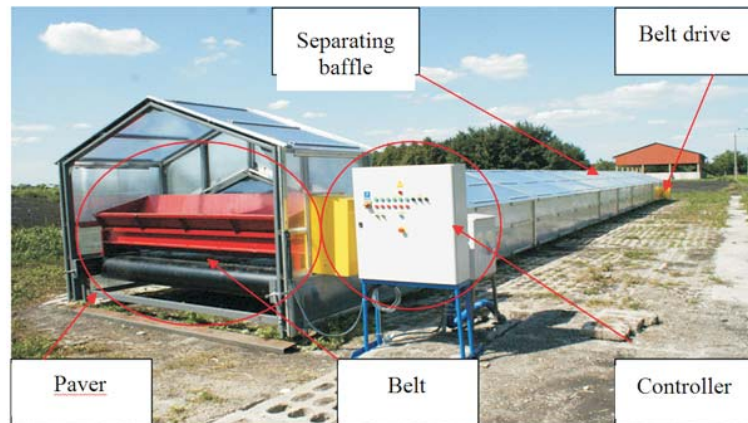


Figure 2. A view of the test system.



Figure 3. A view of the test system.

### 3.2 Drying process investigation

The test programme included continuous recording of:

- ambient air (as charged into the facility) temperature and humidity,
- temperature and humidity of air discharged from the facility – single thermal-hygrometer at the discharge from each drying facility section,
- continuous measurement of the weight of sludge remaining on the belt area over the scale installed below,
- dry mass content and humidity of the dried sludge – samples analysed in the treatment plant's laboratory.

Air temperature and relative humidity, both for intake and discharge air, were recorded with a 5 minute resolution. Measurement results have been used to analyse character of drying rate changes in daily periods.

## 4 Measurement results

In order to verify the theoretical discussion presented in Section 2, analysis of experimental data obtained at Błonie sewage sludge drying facility has been performed. More than twenty measured drying cycles have been recorded during the analysed operating period of the drying facility (first half of 2012). During each cycle the system worked at constant air flow of 12.000 m<sup>3</sup>/h blown into each of two sections. Initial mass of the sludge,  $I_m$ , on the belt surface varied, depending on a drying cycle, from 5.1 to 20 kg/m<sup>2</sup>. Values of the cumulative drying potential with a time resolution of 5 seconds were calculated according to the algorithm presented in the Section 2 using collected data on air parameters. Amount of water evaporated from the mass of dried sludge was determined using measurements of sludge mass remaining on a specific section of the belt. Weight values were read out by an operator every two hours.

Due to considerable differences in the initial mass of dried sludge, the data was divided into three groups. Drying cycles were assigned to those groups according to the initial mass  $I_m$ :

- group I – with  $I_m$  from 5 to 8.3 kg/m<sup>2</sup>,
- group II – with  $I_m$  between 8.3 and 12.5 kg/m<sup>2</sup>,
- group III – with  $I_m$  between 12.5 and 20 kg/m<sup>2</sup>.

The evaporated water  $m_w$  as a function of a cumulative potential  $S$  for each of the data groups listed above is presented in diagrams (Figs. 4–6).

These diagrams confirm a clear relation, as proposed in theoretical discussion, between the cumulative drying potential of ventilation air and mass of evaporated water.

Values of correlation coefficients for the proposed groups confirm good dependency:

- group I – 0.912,
- group II – 0.774,
- group III – 0.889.



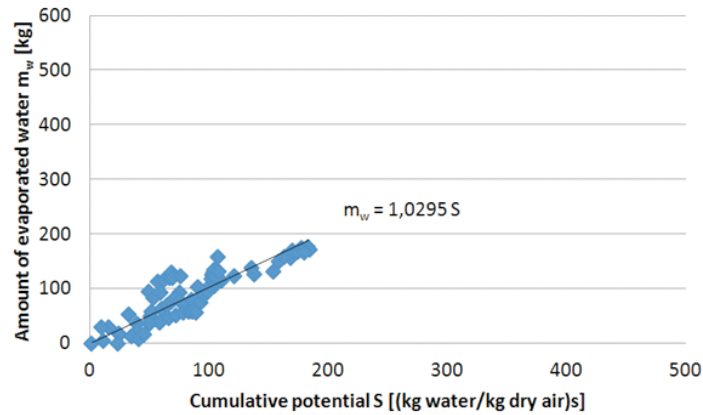


Figure 4. Evaporated water mass  $m_w$  as a function of the cumulative drying potential of the ventilation air  $S$ . Data for drying cycles for which  $I_m$  was between 5 and 8.3 kg/m<sup>2</sup>.

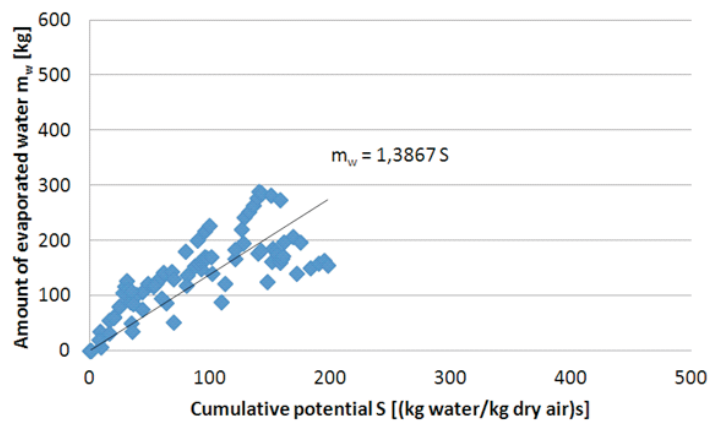


Figure 5. Evaporated water mass  $m_w$  as a function of the cumulative drying potential of the ventilation air  $S$ . Data for drying cycles for which  $I_m$  was between 8.3 and 12.5 kg/m<sup>2</sup>.

As already mentioned, the presented discussion is only valid as long as the dried matter remains in the first drying period. It seems that differences in inclination of the curve depicting discussed dependency which occur between the individual data groups may result from various adherence to this condition. For the data from the first group amount of sludge in the drying

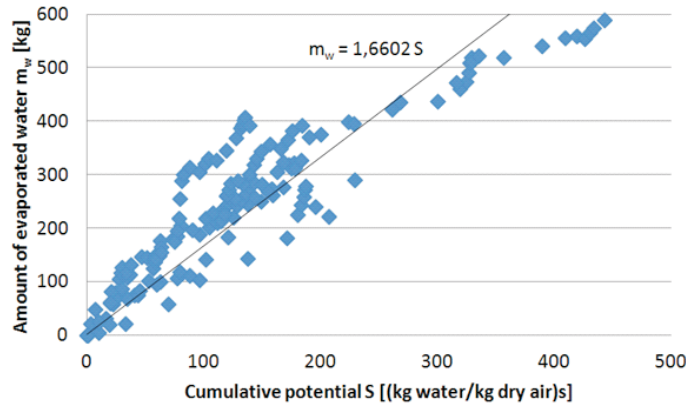


Figure 6. Evaporated water mass  $m_w$  as a function of the cumulative drying potential of the ventilation air  $S$ . Data for drying cycles for which  $I_m$  was between 12.5 and 20  $\text{kg}/\text{m}^2$ .

facility is so low, that the same amount of evaporated water results with a higher share of dry mass than in case of a large initial sludge mass. In such a case overdrying may occur, especially locally, and lead to material passing into the second drying period. Analysing of the group III data reveals that the same value of cumulative potential leads to evaporation of higher water mass than in case of group I. Dried matter remains more humid after evaporation of the same water mass, and thus it remains further from the second drying period, even locally.

Knowledge of the amount of water evaporated from the dried sludge matter, which is a function of a cumulative drying potential of the ventilation air, allows determining current average content of dry mass in the dried matter. This may be done with the following relation:

$$dm = \frac{I_{dm}}{1 - \frac{m_w(S)}{A I_m}} . \quad (15)$$

Hence presented approach above allows to get approximate information on the current content of dry mass in the dried matter, using only data on current and historical ventilation air parameters. This knowledge may be used for example to exercise better control on the drying process. It is possible for example to make:

- drying facility belt travel speed dependant on a cumulative ventilation air drying potential – in case of systems with continuous belt movement,

- moment of unloading dried sludge from the facility and forming a new deposit dependant on a cumulative ventilation air drying potential – for systems with continuous belt movement.

## 5 Conclusions

Discussion presented in the paper shows that it is possible to link properties of the ventilation air supplied to a drying facility to the current dry mass content in the dried matter. Presented method allows determining dried matter conditions at any moment of the drying process without collecting samples and analysing them. Proposed approach is based on the indirect method. Result obtained is the average dry mass content in the whole bulk of dried matter (sewage sludge). Accuracy of this indirect method is however lower than that of direct measurements, and it is applicable only if certain conditions are fulfilled (drying process mainly within the first drying period). Nevertheless its simplicity, fact that no additional instrumentation is required and availability of current result at any moment of time support its application in drying facilities with a design similar to the analysed unit (solar and air-flow drying facilities).

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