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Control strategy for ventilation system of sewage sludge solar dryer

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Abstract

Control of low-temperature drying facilities using unprocessed air causes multiple difficulties due to major variability of ventilation air properties, both daily and seasonal. This paper presents an analysis of operating parameters of a sludge solar drying plant based on an approach that uses the concept of ventilation air drying potential. Formulas for the drying rate as a function of temperature and humidity of the ventilation air are given. Analysis results are used to propose recommendations for control strategy for such facilities aimed at improving efficiency and lowering power consumption. The analytical work was based on experimental data collected during operation of a test solar sludge drying facility located at a waste water treatment plant in Skarżysko-Kamienna (Central Poland).

Keywords: sewage sludge drying, solar drying, ventilation system control

1. Introduction

Despite the growing popularity of solar drying facilities dedicated to sewage sludge drying, research papers describing thermal and flow phenomena occurring at such facilities are still scarce. There are also few recommendations for design and control of such plants. This situation is caused by the fact that there are very few suppliers of such facilities and they most likely are not particularly interested in disseminating expert knowledge, as well as the special nature of this type of facility, which differs considerably depending on local conditions. This paper proposes a universal control strategy for a ventilation system of a solar sewage sludge drying facility based on a theoretical discussion combined with experimental testing. The goal of the new control method is obtaining high efficiency of the facility, understood as the ratio of the amount of evaporated water to the electricity consumption needed to drive the fans.

2. Drying potential of the ventilation air

Drying humid materials involves the simultaneous transfer of heat and mass, both inside the dried matter and within the boundary layer, at the phase boundary and in the flowing gas. Under conditions of the first drying period, the most important transfers occur in the boundary layer, while during the second period additional resistance attributable to transfer processes occurring within the dried matter also arises. During the drying process, the vaporized liquid diffuses through the boundary layer formed at the surface of the dried matter to the environment [1, 2]. Research [3, 4] studies indicate that the critical value at which the drying process passes from the unbound water to the bound water phase (second drying period) is approximately 0.3 kg water/kg dry mass, i.e., ca. 23% of water by mass. Sewage sludges delivered to a drying facility typically have a humidity of some 4 kg water/kg dry mass, i.e., a moisture content of some 80%. Those which leave the facility typically have a moisture content of 20-25%. The process of sewage sludge drying in solar facilities is therefore fully contained within the first drying period. The rate at which humidity evaporates from the dried matter may be expressed as [5–7]:

$$W = A\,k_y\,(Y_s - Y) \tag{1}$$

where: W—drying rate, A - surface area, k_y—mass transfer coefficient, Y_s—moisture content in saturated air, Y—moisture content in the main air flow. Moisture content Y_s equals the moisture content in saturated state at the temperature of the liquid layer which covers the dried matter t_s, and it depends on the value of this temperature. The water evaporation process is driven by the difference between the moisture content in the air which is in contact with the dried matter Y_s and the moisture content in the main air flow Y. The value of mass transfer coefficient k_y mainly depends on hydrodynamic conditions of the process [3]. The depth of mass penetration at the boundary layer, which determines the value of

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k_y depends on the linear velocity of gas above the dried matter according to the relation: $k_y \approx U^{0.8}$ [8]. When considering a drying facility with a known active surface area of the dried matter, and constant settings of the ventilation system which are not adjusted during the process, we may assume that:

$$A\,k_y = C = const. \tag{2}$$

where: C—constant. In such a case the drying rate depends only on the driving force of the drying process. According to the drying theory for the constant drying rate phase (first drying period), the temperature of matter's surface in contact with the air is constant and equal to the wet bulb temperature for ventilation air parameters [8, 9]. Thus following the drying theory it is possible to determine the temperature of the dried matter surface $t_s = t_m(t_z, \varphi_z)$, and subsequently the moisture content in the air in contact with the dried matter $Y_s = Y_m$, based just on the known temperature and humidity of the ventilation air. Therefore it is possible to determine the theoretical magnitude of the driving force of the drying process which would occur under conditions of the first drying period when air of known temperature and relative humidity is used. For the sake of this paper, this value is defined as the drying potential of ventilation air P_Z.

$$P_Z = Y_m(t_m, \varphi = 100\%) - Y_Z \tag{3}$$

where: P_Z—drying potential of the ventilation air, Y_m—moisture content at the wet bulb temperature (t_m) and at saturation conditions (φ=100%), Y_Z—moisture content in ventilation (ambient) air. The conclusion from this discussion is that the momentary drying rate should be proportional to the momentary humidity recovery potential of the ventilation air.

$$W = C\,(Y_m - Y_Z) = C\,P_Z \tag{4}$$

The discussion presented above is valid as long as the dried sludge remains within the first drying period [7, 10]. In the further part of this paper, the discussion above will be compared to the actual measurement data collected during operation of a solar sewage sludge drying plant in Skarżysko-Kamienna.

3. Skarżysko-Kamienna test facility

The essential design characteristics of the Skarżysko-Kamienna drying facility are presented in [6, 11, 12]. A typical gardening tunnel structure, 60 m long and 9 m wide, is set on a hard surface. The tunnel cover is made of 8 mm thick monocular polycarbonate panels. The ventilation system of the drying facility is configured in a way ensuring that air is blown perpendicularly to the drying surface. The Skarżysko-Kamienna drying facility uses a railed sludge spreader with a span of 8 m.

4. Measurement results

The test programme involved continuous recording of parameters including temperature and relative humidity of ambient air (blown into the facility) and exhaust air. Determination of solar radiation flux density was based on our own measurements and data obtained from a meteorological station operated by LAB-EL company for the Ursus district of Warsaw. The results presented in this paper cover one full drying cycle carried out during summer. The dried matter was ca. 80 Mg of dehydrated, digested sludge with 80% moisure content. During the entire cycle, the facility operated at constant parameters: air flow, and spreader operation. Most days of the cycle allowed direct action of the sun and featured relatively high ambient air temperatures. During the 17-day process, sludge moisure content was reduced from 80% to 21% after evaporation of ca. 60 Mg of water.

5. Analysis of measurement results

The aim of the analysis was to use the measurement data from the test facility to find a correlation which would then enable us to determine the momentary value of the drying rate for this kind of plant from ambient data (like humidity and temperature of ambient air). According to the theoretical discussion presented above, the momentary drying rate should be directly proportional to the momentary drying potential of ventilation air P_z. On the other hand, when the measurement data is available, the drying rate may be expressed as a product of the increase in moisture content in the ventilation air, and flow of that air—5. This leads to an equation according to which the increase in the moisture content in the ventilation air should be proportional to the momentary drying potential of that air—6.

$$W = m_a\,(Y_{out} - Y_Z) = C\,P_Z \tag{5}$$

$$(Y_{out} - Y_Z) = \varDelta Y = \frac{C}{m_a}\,P_Z \tag{6}$$

where: m_a—mass flow of the ventilation air, Y_{out}—moisture content at the ventilation air exhaust from the facility. The Fig. 1 presents the postulated relation using the measurement data from the analyzed drying cycle.

Analysis of the charted data (Fig. 1) allows one to conclude that there is a proportional relation between the increase in the moisture content in the ventilation air (which illustrates the momentary drying rate) and the momentary value of the ventilation air drying potential. The correlation coefficient between the data sets is above 0.78. The presented relation may be approximated by the following linear function 7:

$$\Delta Y = 0,747\,P_Z + 3,85e^{-4} \tag{7}$$

The presented theoretical discussion concerning the linear relation between the drying rate and humidity recovery potential of the ventilation air is based on the isenthalpic

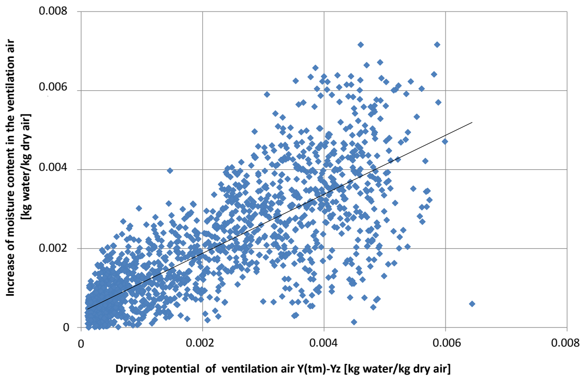

Figure 1: Increase in moisture content in the ventilation air as a function of drying potential for that air during the analyzed operating cycle of the test facility—experimental data

character of the drying process. In the case of a solar drying facility, especially at midday, this condition is not met. Air enthalpy at the facility outlet is higher than that of the incoming air. This is due to the fact that additional energy is supplied by solar radiation. In order to estimate the momentary drying rate in a simplified manner for the needs of plant control it suffices to know just the ventilation air parameters. A more comprehensive analysis should also take into account the intensity of solar radiation inside the facility [13].

6. Recommendations concerning control of a ventilation system in a solar sludge drying facility

According to the presented results of the analysis, in the case of a ventilation system operating at a solar sewage sludge drying facility, it is justified to set a minimum threshold of drying potential at which the ventilation system should start. Our own analysis indicates that in Polish conditions for the most part of the year the drying potential of ambient ventilation air is unsatisfactory and operation of the ventilation system in a solar drying facility and of the whole drying facility is not justified. In such a case it only consumes electricity without ensuring the possibility of removing humidity from the sludge. The threshold value of ventilation air drying potential is difficult to set in a universal manner that is valid for all potential operators of solar drying facilities. Each operator may work in different market conditions and have different priorities when operating its own system. According to the presented results of research, it seems unjustified to keep a solar drying facility operating when the ventilation air drying potential is below 0.0015. Often, at existing solar drying plants for sewage sludge, there is an extensive ventilation system consisting of:

- mixing fans—parallel to the dried matter, ensuring air flow above the surface;
- exhaust fans and ventilation flaps—ensuring exchange of air inside the hall.

In such a case, the ventilation controls system should not only control start-ups and shutdowns of the system, but also the mode of operation. The following possibilities exist:

- system offline, neither mixing fans nor exhaust fans operate;
- mixing fans online, exhaust fans offline;
- mixing and exhaust fans online.

A ventilation system's control algorithm should be able to decide when to start the exhaust fans to ensure air exchange inside the facility. Based on the presented results of research, the following algorithm can be proposed:

- The drying potential of ambient and internal air is determined from measurements of temperature and humidity of the air inside and outside the hall.
- Calculated potential values are compared. If the potential of the interior air is higher than that of ambient air, then the ventilation air within the hall should not be exchanged. Otherwise, the exhaust fans responsible for air exchange in the hall should start for a certain time.
- If the calculated value of drying potential for both internal and ambient air is below the threshold value, and such a condition persists for a pre-set amount of time, the drying facility should be shut down.

The proposed algorithm should enable optimal operation of the ventilation system within a solar drying facility for sewage sludge, regardless of local weather conditions.

7. Summary

Discussion presented in the paper indicates that it is possible to link the properties of ventilation air fed into a drying facility to the current drying rate. This was done based on an approach that involves the concept of drying potential of ventilation air. The relation obtained as a result of research enables one to:

- evaluate the actual efficiency of the drying facility in any weather conditions;
- determine the required surface area of a new drying facility for assumed capacity and local climate conditions;
- determine minimum levels of ventilation air parameters above which it is justified to run the drying process. As a result it is possible to shorten the operating time of the process systems within the facility and to reduce specific electricity consumption.

Basing on the analysis results, recommendations were given for control strategy for this kind of facility which would lead to higher efficiency and lower specific electricity consumption. The analysis was based on experimental data collected during the operation of an experimental solar sewage sludge drying facility located in Skarżysko-Kamienna, Central Poland.

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