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Modeling of thermal and flow processes in a solar waste-water sludge dryer with supplementary heat supply from external sources

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Abstract

This article presents a continuation of previous research on a model of solar waste-water sludge drying processes. The primary premises for that model were described in [1, 2]. This paper presents results from a simulation of a drying process powered by solar radiation energy supplemented with external heat delivered to the dried matter through an IR heating lamp installation and floor heating system. The modeling results were used to discuss the impact of individual heat delivery systems on the primary performance parameters of the drying facility (primarily its efficiency) as well as on the operation of the ventilation system and sludge shuffling installation. Appropriate shuffling frequency has a significant impact on both the efficiency of the facility and its electricity consumption.

Another analyzed parameter was effectiveness of supplementary heat usage, both for the IR lamp system and the floor heating system.

Keywords: waste-water sludge drying, CFD, solar drying, heat exchange, mass exchange.

1. Introduction

In 2005 the Institute of Heat Engineering, Warsaw University of Technology developed a concept of a solar waste-water sludge dryer. A pilot facility was constructed in keeping with that concept in a waste-water treatment plant in Skarżysko-Kamienna, Poland.

The facility is located inside a light steel structure covered with polycarbonate plates constructed on a concrete plate. The structure was fitted with a ventilation system and a sludge shuffling system was installed. The ventilation system was designed to provide uniform air distribution over the surface of the dried sludge through a number of blowers. Details about the Skarżysko-Kamienna waste-water sludge drying facility can be found in [3, 4].

To gain greater insight into the drying process the authors of the article developed a mathematical model mapping out the kinetics of the waste-water sludge solar drying process in the conditions of the first and second drying phases.

The proposed model included heat and mass transport:

- within the dried matter (waste-water sludge);
- within the ambient air;
- on the border between those two areas.

The thermal and flow processes occurring inside the dryer were viewed as unsteady due to the fact that the thermodynamic characteristics of the sludge

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as well as drying conditions (intensity of solar radiation, temperature and humidity of ventilation air) change over time. The model also took into account the impact of the shuffling installation's operation on the thermal and flow processes inside the facility. A detailed description of this model can be found in [1] and [2].

The model was solved using commercial Fluent 6.2.16. CFD software based on the Finite Volume Method with a custom-made User Defined Function implemented.

As the solar sludge drier has considerable cubic capacity, modeling it as a whole would require high computing power. Therefore only one section was modeled – the area affected by a single blower.

This article presents results achieved with the model when used to simulate waste-water sludge solar drying with supplementary external heat delivered to the dried matter through a system of IR lamps and through floor heating.

2. Modeling results

To determine the impact of the supplementary heating systems on the performance of the solar drying facility, calculations for a 24-hour period were carried out in three variants:

- purely solar drying (as a reference);
- solar drying with supplementary infrared lamp heating (150 W/m^2);
- solar drying with supplementary floor heating at a floor temperature of 50°C.

The input parameters used were real weather data (solar radiation intensity, relative humidity and ambient air temperature) recorded on a selected day in June. All the simulation cases assumed constant frequency of sludge shuffling – once every 2 hours.

2.1. Solar drying with infrared lamps

The simulation results indicate that supplying additional energy to the layer of dried sludge in the form of infrared radiation increases the average daily drying rate from 8.12 kg H_2O/m²d (for solar-only drying) to 11.11 kg H_2O/m²d. An increased drying rate was observed throughout the whole period (Fig. 1). Analysis of the chart (Fig. 1) indicates that using IR lamps enhances the effect of "drying rate peaks" after each shuffling during the daytime and weakens it at night. This behavior seems correct because during the day the additional energy supplied to the surface increases the temperature difference between the surface and average sludge temperature, while at night it decreases it.

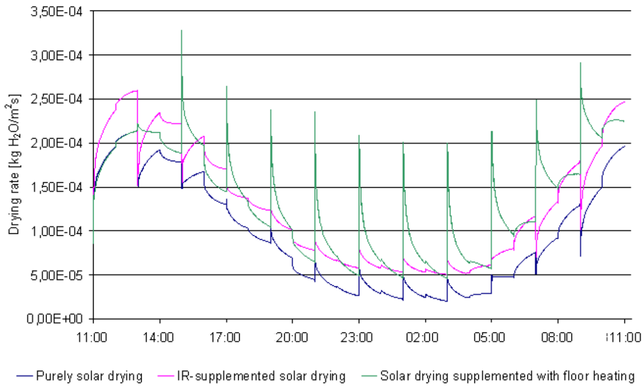

Figure 1: Comparison of drying rate curve for purely solar drying, IR-supplemented solar drying and solar drying supplemented with floor heating

According to the simulation results the usage efficiency of the heat from IR lamps for drying process η was:

$$\eta = \left(\frac{\triangle W \cdot r}{P \cdot 86400}\right) \cdot 100 = 57.7\% \qquad (1)$$

where:

$\triangle W$ – increase in the daily drying rate when using IR lamps, referenced to purely solar drying;

$P = 150$ W/m^2 – assumed power output of the IR heating.

The supplementary heat demand to evaporate 1 Mg of H_2O in the analyzed case was ca. 4.3 GJ. It is therefore higher than the values encountered in classic sludge drying facilities. During the drying process with IR heating the average temperature of the dried sludge layer rises (Fig. 2). Using the IR lamps leads to a significant rise in the temperature of the wet surface, resulting in higher vapor pressure in the air near the dried matter and therefore a faster drying rate (Fig. 3).

The faster drying rate means the surface is better dried between the shuffling procedures. This leads to decreased water activity (second drying phase) and a lower local drying rate. This situation is shown in Fig. 3. Increasing the shuffling frequency prevents

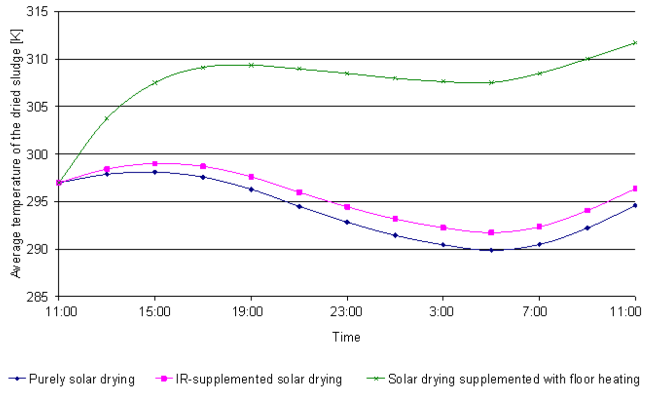

Figure 2: Comparison of average temperature of the dried sludge layer during the modeled days – for purely solar drying, IR-supplemented solar drying and solar drying supplemented with floor heating

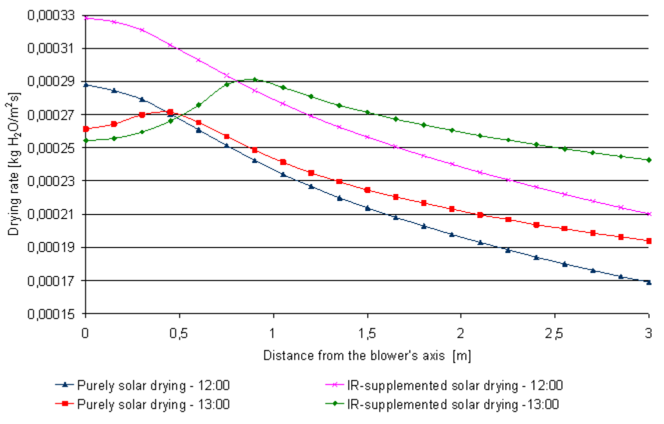

Figure 3: Comparison of the dependency between the drying rate and distance from the blower's axis for various hours of the modeled day – for purely solar drying, and for IR-supplemented solar drying

excessive local drying.

The higher temperature of the wet surface caused by the use of IR lamps raises the temperature of the adjacent air, which is a loss for the drying process.

2.2. *Solar drying with supplementary floor heating*

The average power of the floor heating system resulting from the assumed constant floor temperature of 50°C was 225 W/m^2.

The modeling results indicate that operating the floor heating system at such parameters increases the average daily drying rate from 8.12 kg H_2O/m²d (for purely solar drying) to 11.71 kg H_2O/m²d. According to the simulation results the efficiency of using the heat delivered by the floor heating system for drying process η was:

$$\eta = \left(\frac{\triangle W \cdot r}{P \cdot 86400}\right) \cdot 100 = 46.2\% \qquad (2)$$

where:

$\triangle W$ – increase in the daily drying rate when using the floor heating system, referenced to purely solar drying;

$P = 225$ W/m^2 – resulting average power output of the floor heating system.

The supplementary heat demand to evaporate 1 Mg of H_2O in the analyzed case was ca. 5.4 GJ. Therefore, at the assumed operating parameters of the drying facility, the heat supply through the floor heating system turned out to be a less efficient method of supplementing the solar drying than using the IR lamps.

Analysis of the chart (Fig. 1) shows that sing the floor heating system reverts the effect of "drying rate peaks" which occur after each shuffling during the day but intensifies it at night. This happens because in this situation the average temperature of the sludge layer is always higher than that of the surface. Thus each shuffling results in a temporary significant increase in the drying rate.

Using the floor heating system (at assumed heating conditions) results in a very high increase in the average temperature of the sludge layer in comparison to both (i) purely solar drying, and (ii) IR-supplemented drying (Fig. 2). The surface temperature – depending

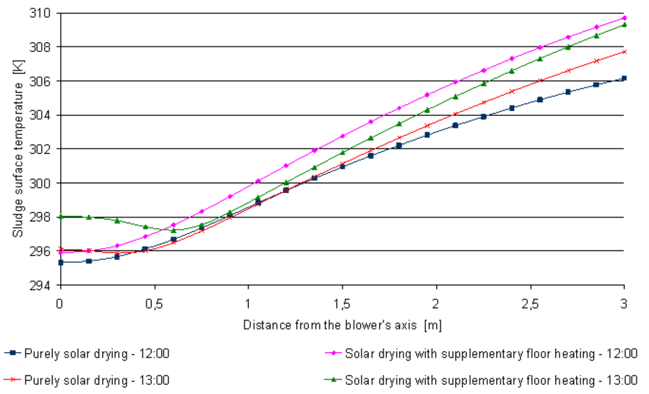

Figure 4: Comparison of the dependency between the sludge surface temperature and the distance from the blower's axis for various hours of the modeled day – for purely solar drying and solar drying with supplementary floor heating

on time elapsed since shuffling – approaches the values typical for purely solar drying – this phenomenon can be observed in Fig. 4.

3. Analysis of the modeling results

Using as a basis the achieved results of modeling the process of solar waste-water sludge drying with supplementary IR lamps, it can be stated that use of those lamps:

- significantly increases the surface temperature and drying rate (both day and night)
- causes an increased average temperature of the sludge layer and adjacent air
- requires adaptation of the shuffling pattern to the increased drying rate.

IR lamps appear to be a relatively cheap and effective solution for supplementing solar energy with external heat. Supplementary heating of the sludge layer however requires expensive heat carriers such as natural gas, biogas, fuel oil or electricity. This can lead to a significant rise in the operating costs of the drying facility.

The modeling results illustrate the key role played by the shuffling installation when using floor heating system. In contrast to its use in purely solar or solar-IR methods, here its function is twofold: (i) to deliver wet sludge to the surface (for contact with the ambient air) and (ii) to supplement heat transportation from the warmed-up bottom to the surface.

Since in this configuration of the drying facility each shuffling procures a temporary increase in the drying rate, the shuffling frequency should be as high as possible to maximize this phenomenon.

One last advantage of floor heating over the IR lamp system is the possibility of using it in drying facilities which have access to a low temperature heat source, although this inevitably increases the investment cost.

4. Conclusions

Analysis of the results obtained from the simulation of solar drying with a supplementary heat supply leads to the conclusion that the usage effectiveness of the supplementary heat (in both cases – IR lamps and floor heating) is significantly lower than for other types of drying facilities. Therefore from the energy balance point of view it is not advisable to construct solar sludge driers with high supplementary heating capacity through external sources. In such cases benefits from the "free" solar energy could be "cancelled" by the losses in a low-efficiency external heat supply system (it can be compared to for instance moving belt driers, where the specific heat demand is approximately 3.2 GJ/Mg of extracted water).

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