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ScienceDirect

Procedia Engineering 157 (2016) 230 – 237

Procedia Engineering

www.elsevier.com/locate/procedia

IX International Conference on Computational Heat and Mass Transfer, ICCHMT2016

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.

Peer-review under responsibility of the organizing committee of ICCHMT2016

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

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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Peer-review under responsibility of the organizing committee of ICCHMT2016
doi:10.1016/j.proeng.2016.08.361

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