Water Research 95 (2016) 340–347

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Effect of foam on temperature prediction and heat recovery potential from biological wastewater treatment

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ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form
30 January 2016
Accepted 13 March 2016
Available online 16 March 2016

Keywords:
Foam
Heat balance
Heat recovery
Lab-scale experiment
Modeling
Simulation

ABSTRACT

Heat is an important resource in wastewater treatment plants (WWTPs) which can be recovered. A prerequisite to determine the theoretical heat recovery potential is an accurate heat balance model for temperature prediction. The insulating effect of foam present on the basin surface and its influence on temperature prediction were assessed in this study. Experiments were carried out to characterize the foam layer and its insulating properties. A refined dynamic temperature prediction model, taking into account the effect of foam, was set up. Simulation studies for a WWTP treating highly concentrated (manure) wastewater revealed that the foam layer had a significant effect on temperature prediction (3.8 ± 0.7 K over the year) and thus on the theoretical heat recovery potential (30% reduction when foam is not considered). Seasonal effects on the individual heat losses and heat gains were assessed. Additionally, the effects of the critical basin temperature above which heat is recovered, foam thickness, surface evaporation rate reduction and the non-absorbed solar radiation on the theoretical heat recovery potential were evaluated.

1. Introduction

The increasing scarcity of fossil energy resources and the need for reducing greenhouse gas emissions related to climate change have made renewable energy and energy efficiency an important issue in our society. Many efforts have been done to take advantage of the energy carried out by wastewater—from its point of generation to its point of treatment and discharge to the environment. Meggers and Leibungut (2011) and Cipolla and Maglionico (2014) studied the potential heat recovery from water in buildings. Dürrenmatt and Wanner (2014) developed a mathematical model to predict the effect of heat recovery on the wastewater temperature in sewers. In WWTPs, heat is an important resource which is generated during biological conversions and creates an opportunity for heat recovery from these systems, improving the energy use of the plant. The potential heat recovery increases with increasing biological heat production, i.e. for wastewater with high concentrations of organic matter and/or nitrogen. Nevertheless, activated sludge systems treating highly concentrated wastewater rarely operate at temperatures above 35–40 °C, which is rather low for practical applications. In order to increase the temperature of the available heat and so its usefulness, heat recovery from biological treatment processes can be performed with heat pumps (Hughes, 1984; Svoboda and Evans, 1987). The recovered heat could be applied to fulfill diverse heating requirements, e.g. heating of buildings and greenhouses.

To reliably estimate the heat recovery potential from a WWTP, a heat balance needs to be set up to calculate its temperature. The application of heat balances for the dynamic prediction of basin temperature has been demonstrated previously by, for example, Sedory and Stenstrom (1995) and Makinia et al. (2005). In another study, Gillot and Vanrolleghem (2003) compared two prediction models to obtain the equilibrium temperature in aerated basins which differed in their degree of complexity. Fernandez-Arevalo et al. (2014) presented a systematic methodology to incorporate heat transfer modeling in multi-phase biochemical reactors, enabling the dynamic description of mass and heat in a plant-wide context.

However, the influence of a foam layer on the heat balance of a WWTP has not been accounted for in literature so far. Foam formation is often observed on the surface of aeration basins of activated sludge systems, especially when treating concentrated wastewater. A foam layer can provide significant insulation

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http://dx.doi.org/10.1016/j.watres.2016.03.031
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(Cumby, 1987). Hughes (1984), for example, observed relatively high water temperatures in a large open topped lagoon during winter time and attributed these to the foam layer formed on the lagoon surface.

In this study, dedicated experiments were performed to characterize the foam and its insulating properties. The heat balance model was extended accordingly to account for foam formation on basin surfaces. The influence of foam on temperature prediction and on the heat recovery potential from a WWTP treating highly loaded wastewater was subsequently analyzed through simulation over a one-year period. A sensitivity analysis was performed to evaluate the influence of process parameters.

2. Materials and methods

2.1. Heat balance over a wastewater treatment basin

The heat balance (Eq. (1)) over a completely mixed basin with a constant volume V (m^3) expresses that heat accumulation, reflected by an increase of the basin temperature T_w (K) with time, t (s), results from advective heat transport H_{eff} (W) and the net heat exchange ΔH (W) over the basin.

$$\rho_w V c_{pw} \frac{dT_w}{dt} = H_{eff} + \Delta H \quad \left[J \cdot s^{-1} = W\right] \tag{1}$$

ρ_w (kg m^{-3}) denotes the density of the wastewater and c_{pw} (J kg^{-1} K^{-1}) its specific heat capacity. H_{eff} represents the heat required to bring the influent temperature (T_i) to the basin's temperature (T_w):

$$H_{eff} = \rho_w Q_w c_{pw} (T_i - T_w) \quad \left[J \cdot s^{-1} = W\right] \tag{2}$$

with Q_w (m^3 s^{-1}) the wastewater flow rate and T_i (K) the influent temperature. It was assumed that the density and specific heat capacity of the influent, basin and effluent were the same and constant through time. Furthermore, flow rate changes due to evaporation were neglected.

The net heat exchange (Eq. (3)) over the basin was represented by a sum of heat fluxes (see Fig. 1A):

$$\Delta H = H_{sr} + H_p + H_b - H_{ar} - H_{ev} - H_c - H_{tw} - H_{ae} - H_{hr} \quad \left[J \cdot s^{-1} = W\right] \tag{3}$$

where a positive or negative sign represents a heat gain or loss, respectively. The absorbed solar radiation (H_{sr}) was considered to be the available radiation on flat surfaces given in the typical reference year dataset from Belgium (Dogniaux et al., 1978). The power input (H_p) was derived from sub-surface aeration (Sedory and Stenstrom, 1995). The heat from biological reactions (H_b) comprised the heat from nitrification (H_{nit}), denitrification (H_{denit}) and organic degradation (H_{COD}). Atmospheric radiation (H_{ar}) was based on the Stefan-Boltzmann's law to describe the long-wave heat exchange between the basin and the sky. Surface evaporation (H_{ev}) and convection (H_c) were based on the dimensionless number analysis of forced convection in parallel flow over flat surfaces. Heat exchanges through the basin wall and bottom (H_{tw}) were calculated with an overall heat transfer coefficient. The sensible and latent heat lost due to aeration (H_{ae}) represents the heat required to bring aeration air to basin temperature and water evaporation as this airflow gets saturated (Sedory and Stenstrom, 1995). The heat recovery potential (H_{hr}) is the theoretical maximum surplus heat that can be removed from the basin while maintaining an appropriate reaction temperature (T_{crit}). It should be noted that the abovementioned heat losses, exempting H_{hr}, can become heat gains when the environment is at a higher temperature than the system. The complete set of equations is presented in the Supplementary Material, Table S1.

The heat generated during nitrification (H_{nit}) and denitrification (H_{denit}) was calculated taking into account biomass growth, based on the yield coefficients given by (Wiesmann, 1994), as $H_{nit} = 18.9$ MJ $kg_{NH4\text{-}N}^{-1}$ and $H_{denit} = 41.3$ MJ $kg_{NO3\text{-}N}^{-1}$ (at 25 °C, see Supplementary material S1). The heat from organic matter degradation (H_{COD}) originates from the aerobic removal of chemical oxygen demand (COD). To correctly account for the heat generation from organic matter degradation, transformations such as hydrolysis and CO_2 stripping taking place simultaneously need to be considered; they are implicitly included in experimental estimations of heat of reactions (Fernández-Arévalo et al., 2014). Therefore, the value for heat released by organic matter degradation was taken from Blackburn and Cheng (2005), who found a heat production of 13.9 MJ kg_{COD}^{-1} when processing high strength swine waste.

2.2. Foam layer modeling

The heat supplied by the basin to the upper surface of the foam layer (H_f) was assumed to be in equilibrium with the heat lost to the environment at the foam surface (Eq. (4) and Fig. 1B), this considering the small heat capacity of the outermost part of the foam layer in contact with the environment.

$$H_f = H_{ar} + H_{ev} + H_c \quad \left[J \cdot s^{-1} = W\right] \tag{4}$$

The heat exchange via atmospheric radiation (H_{ar}), evaporation

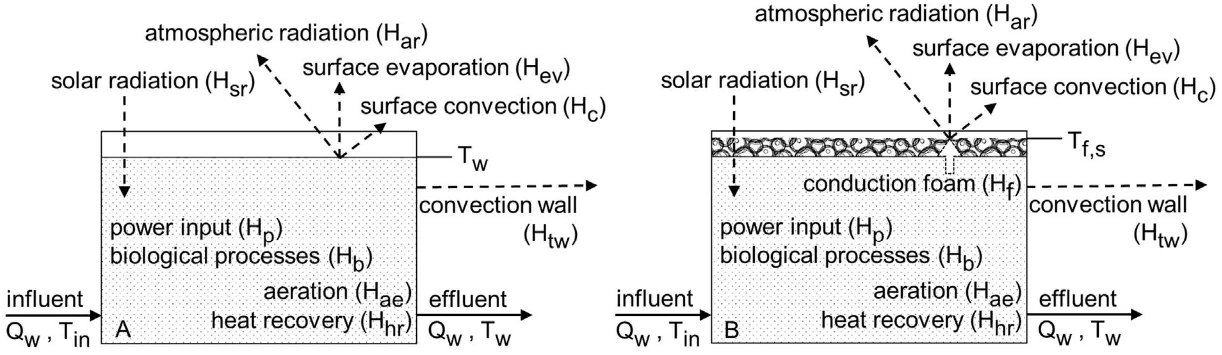

Fig. 1. Heat fluxes acting on an aeration basin: (A) without foam; (B) with foam, where the heat exchanged by the basin to the upper surface of the foam layer (H_f) is equal to the heat exchanged with the environment at the surface (H_{ar}, H_{ev} and H_c).