Proceedings ASCE EWRI World Water and Environmental Resources Congress 2005 May 15-19, 2005

Modeling and evaluating temperature dynamics in wastewater treatment plants

Scott A. Wells[1], Dmitriy Bashkatov[1] and Jacek Makinia[2]

[1] Department of Civil and Environmental Engineering, Portland State University, Portland, OR 97207-0751, wellss@pdx.edu, Voice (503) 725-4276, FAX (503) 725-5950
[2] Technical University of Gdansk, Faculty of Hydro and Environmental Engineering, ul. Narutowicza 11/12, 80-952 Gdansk, Poland, jmakinia@pg.gda.pl

Abstract

With new government regulations governing the discharge of heated effluents into receiving waters, there is much interest in providing a model of temperature dynamics in wastewater treatment plants (WWTP). This type of model would allow operators to evaluate alternatives for reducing effluent temperatures, such as covering secondary clarifiers. This type of tool would also be of use to demonstrate the difficulty in some installations of affecting effluent temperatures.

A model of temperature in a WWTP was developed and tested at a facility in Vancouver, Washington during both summer and winter conditions. Temperatures were taken at 6 control points throughout the treatment plant and used as a basis for model calibration and evaluation. Meteorological data such as air temperature, dew point temperature, wind speed and direction and solar radiation were obtained from nearby weather station. The impacts of the discharge on the Columbia River were also discussed. Also, the basic model was tested in an aeration model using detailed temperature data from a Washington County, Oregon, USA wastewater treatment facility.

Introduction

The U.S Environmental Protection Agency has identified 28,665 waters (USEPA, 2002) in the 50 states that are water quality impaired and listed on the 303(d) list under the Clean Water Act. Impairments due to thermal modifications and temperature alone account for 2,000 of the listed waters.

The discharge of heated effluent from wastewater treatment plants is one concern for temperature regulation in natural waters. Often state regulatory agencies require WWTPs to conduct mixing zone analyses to determine if they violate temperature standards at the edge of the mixing zone. Often if they do, a temperature management plan is required where the WWTP must detail specific heat reduction strategies within the treatment plant or specify additional monitoring to assure compliance with temperature regulations.

The purpose of this paper is to develop the foundation of a temperature model of an entire WWTP with the objective that the model can be used to examine if operational strategies exist within the treatment process to affect the discharge temperature.

Mathematical Modeling of Temperature in a WWTP

In work by Makinia et al. (2005), a basic temperature model was presented for evaluating an aeration basin. This model consists of the dynamic, advective-dispersion equation and a source/sink term for surface heat transfer. This model is described in Appendix A and is the prototype that is being used to develop a model of an entire wastewater treatment plant.

Experimental results were obtained from an aeration basin using the approach in Appendix A. Also, continuous temperatures have been taken at multiple control points in anther wastewater treatment plant to provide the data set necessary to develop and calibrate a rigorous temperature model of an entire wastewater treatment plant.

Rock Creek Aeration Basin Example

The Rock Creek Wastewater Treatment Plant is located in Hillsboro, Oregon (USA) and discharges to the Tualatin River. The Tualatin River is listed as water quality limited for temperature. This river is about 20 m wide and 2 m deep at the Rock Creek discharge during the summer low flow period when the median flow is about 3 m^3/s.

The plant is operated by Unified Sewerage Agency of Washington County and treats wastewater drained by a sanitary sewerage system from a catchment area of 163 km^2. This is primarily domestic wastewater from western Washington County, although some industries (mostly high-technology) discharge their wastewater to the plant.

Some of the treatment processes take place in closed spaces (such as covered primary clarifiers and tertiary treatment in so-called claricones). The secondary treatment process consists of two parallel lines with two activated sludge reactors coupled with circular secondary clarifiers that are open to the atmosphere. The tanks have been designed as six completely mixed zones of equal size. The first zone, further divided into two sub-zones (called Zone 1A and Zone 1B), operates as an anoxic zone during the dry season. Returned activated sludge from the bottom of the secondary clarifier and internal mixed liquor recirculation from the end of the activated sludge reactor can be pumped either to Zone 1A or Zone 1B. Currently, both returned activated sludge and internal mixed liquor recirculation are diverted back to Zone 1A. Air supply to the reactor is controlled by means of oxygen probes installed in Zone 3.

Under dry weather conditions, the daily average flow to the activated sludge reactor is approximately 26,500 m^3/d. During the wet weather season, the flow increases by approximately 100 %. However, the observed daily peak flow during the last three years was 76,000 m^3/d.

Data were collected for evaluation of the temperature model between 06/23-06/24, 1997. The data used for the temperature study included:

- Temperature of incoming wastewater. Automatic readings of the plant influent temperature, recorded at 1-hour intervals, were used as the inflow boundary condition for the temperature model. This assumption appeared to be appropriate because the primary clarifiers at the plant were covered. The observed differences between temperature in the plant influent and the primary clarifier effluent varied during the experiment but did not exceed ±0.1°C.

- Temperature profiles along the longitudinal axis of the activated sludge reactor. During the experiment, temperature was also measured several times in the effluent from each zone of the reactor.
- Meteorological parameters required to solve the heat balance equation. All necessary parameters were available from a nearby meteorological station that recorded at 15 min. to 1-hour intervals.

An example of model predictions compared to field data are shown in Figure 1. Typical model-data errors were on the order of 0.1°C, which were within the accuracy of the temperature probes. Additional details of this study and model-data comparisons are shown in Makinia et al. (2005).

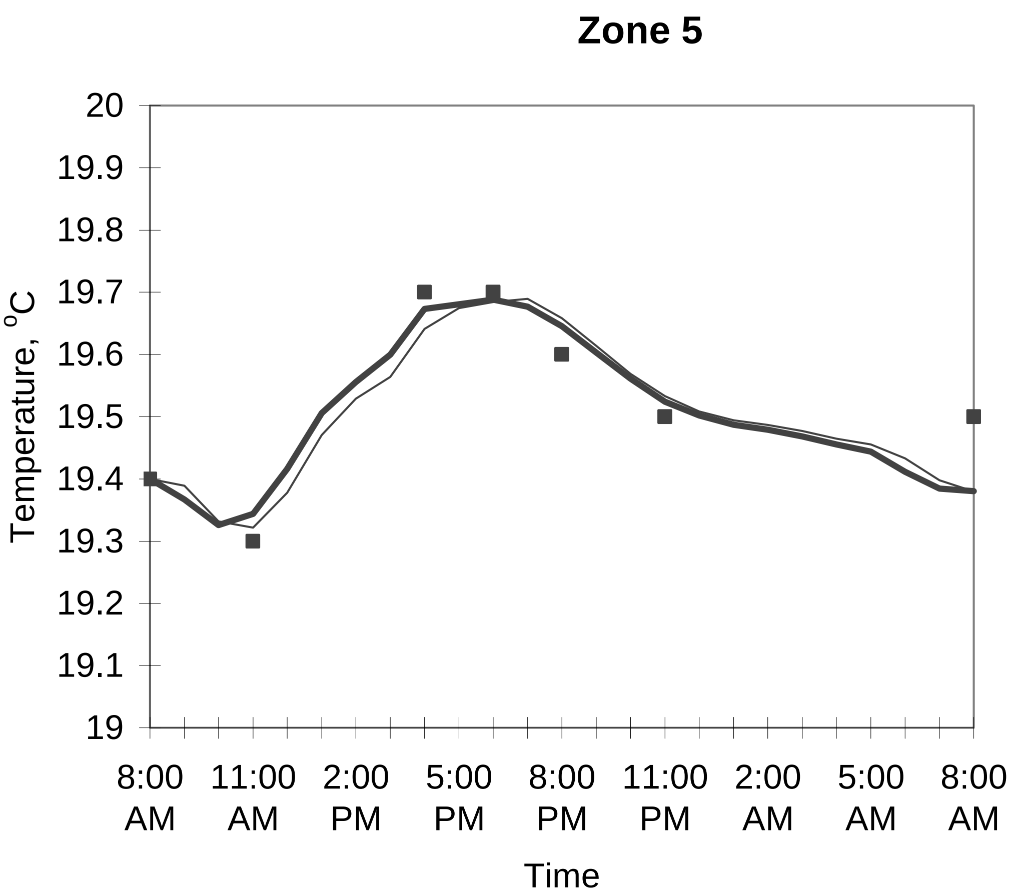

Figure 1. Observed and predicted temperature in effluent from Zone 5 of Aeration Basin 4 during one 24-hour period in 1997.

Salmon Creek Experimental Results

Continuous temperatures at several control points at the Salmon Creek Wastewater Treatment Plant in Clark County, Washington, USA, were measured during the three months of October, November and December of 2004. An aerial view of the plant is shown in Figure 2. Every ten minutes probes recorded temperatures of wastewater at three locations: in the influent channel before the primary clarifiers, in the PE-RAS box where the primary effluent is mixed with the return activated sludge, and in the effluent channel. Since the experiment was conducted during the Fall/Winter season, the results represent a wide range of data. The influent temperatures varied from 20.9°C in October to 12.5°C in December. The plant effluent temperatures also followed this seasonal trend with maximum temperatures of 20.9°C and minimum temperatures of 14.0°C during this period. These data are shown in Figure 3.

Figure 2. Salmon Creek WWTP in Clark County, Washington.

Diurnal fluctuations in ambient temperature and wastewater flow also impacted the wastewater stream. Temperature variations during 24 hour periods were as high as 2.8°C for influent and 1.1°C for effluent (see Figure 4 and Figure 5).

Wastewater was both gaining and/or losing heat while traveling through the treatment plant. The total hydraulic detention time at the SCWWTP averaged around 12 hours during the study. Preliminary analysis of temperature measurements showed that on several days in October wastewater gained as much as 1.5°C during the treatment process. Heat losses in December were as high as 0.5°C.

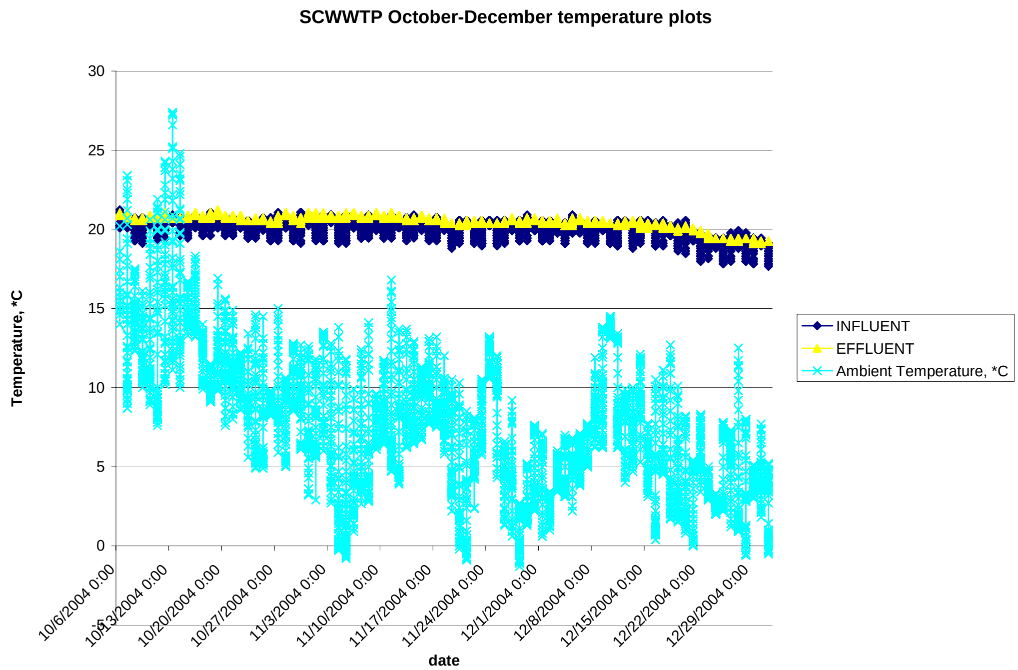

Figure 3. Continuous input and output temperatures from the SCWWTP and ambient air temperatures between October 6, 2004 and December 31, 2004.

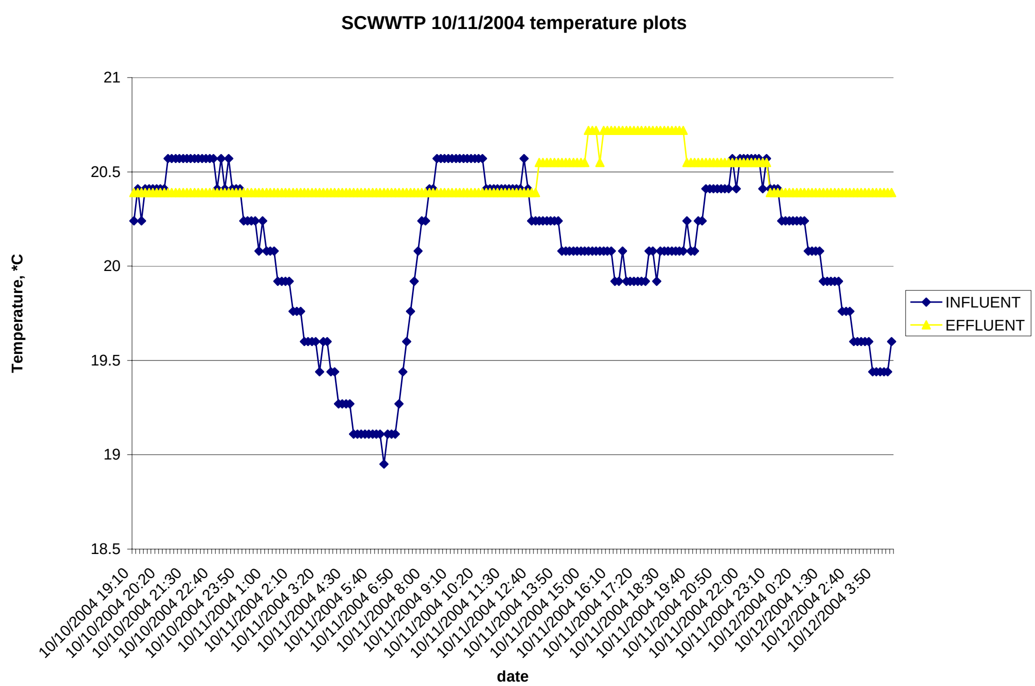

Figure 4. 24-hour variation in influent and effluent temperature for the SCWWTP on 10/10/2004.

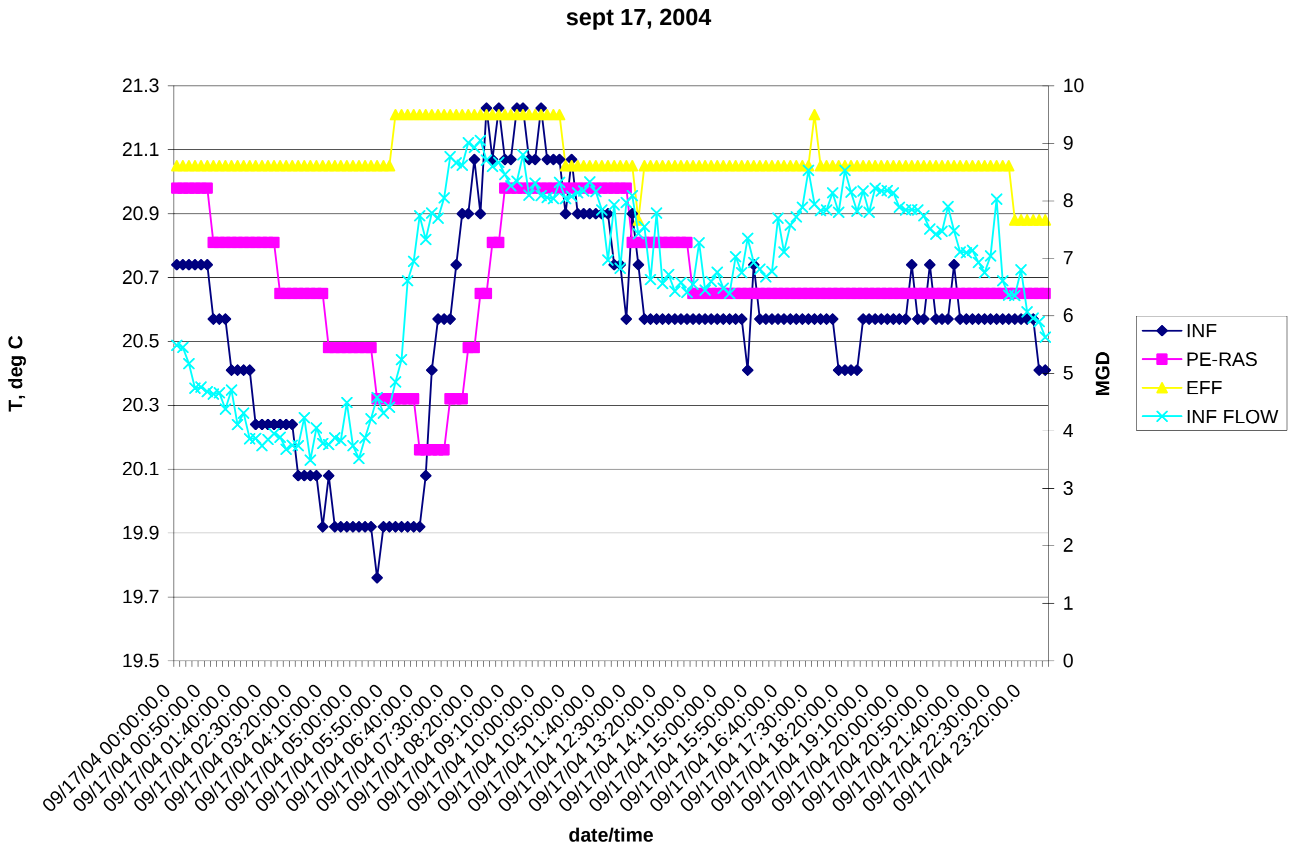

Figure 5. Comparisons over 24 hours of plant flow rate, influent temperature, effluent temperature, and the mixed primary effluent and return activated sludge temperature for Salmon Creek WWTP.

The development of the temperature model for the SCWWTP is continuing for each of the units at the plant:

- Primary rectangular clarifiers (3 units, but usually 2 are on-line at a time)
- Activated sludge basin (4 basins with recycle from the secondary clarifier)
- Secondary circular clarifier (3 units, but usually 2 are on-line at a time)

In addition to developing dynamic temperature models of each unit process, the plumbing of the system needs to be taken into account. This involves accounting for flow splitting and recycling (such as the return activated sludge line and the washwater used after UV disinfection).

Conclusions

A prototype of the wastewater treatment has been developed and tested for an aeration basin with recycle. The next step is to develop the model for individual pieces of the Salmon Creek WWTP in Clark County. The model will be calibrated by comparing model predictions to the field data, such as were presented in this paper. Then the model will be used to evaluate strategies to improve discharge temperatures. Some of these strategies that could be evaluated include covering aeration basins, changing the recycle rate flow rate or location of recycle, and storing and timing of discharges by using dynamic storage. This approach would allow a WWTP to determine the correct approach in developing a temperature mitigation plan if so required by a state regulatory agency.

References

la Cour Jansen, J., Kristensen, G.H., Laursen, K.D. (1992). Activated Sludge Nitrification in Temperature Climate. Wat. Sci. Tech., 25 (4-5), 177-184.

Makinia, J. (1998). Mathematical modeling of the activated sludge reactor with dispersive flow. Ph.D. dissertation, Department of Civil Engineering, Portland State University, Portland, OR (USA).

Makinia, J. and Wells, S.A. (2000). A general model of the activated sludge reactor with dispersive flow: Model development and parameter estimation. Wat. Res 34(16), 3987-3996.

Makinia, J., Wells, S. A., Zima, P. (2005) Temperature modeling in activated sludge systems: a case study, Water Environment Research, in-print.

Scherfig, J., Schleisner, L., Brond, S., Kilde, N. (1996). Dynamic Temperature Changes in Wastewater Treatment Plants. Wat. Env. Res., 68 (2), 143-151.

Sedory, P.E., Stenstrom, M.K. (1995). Dynamic Prediction of Wastewater Aeration Basin Temperature. J. Env. Eng. ASCE, 121 (9), 609-618.

Wells, S.A. (1990). Effect of Winter Heat Loss on Treatment Plant Efficiency. J. Wat. Pollut. Cont. Fed., 62 (1), 34-39.

U.S. Environmental Protection Agency, Office of Water, Watershed Assessment, Tracking and Environmental Results (2002) “National Section 303(d) List Fact Sheet” http://oaspub.epa.gov/waters/national_rept.control (September, 7, 2004).

Appendix A: Mathematical Modeling of Temperature

Transport equation. The transport model is assumed to be the one-dimensional (assuming complete mixing in cross-section) advection-dispersion equation with a heat source/sink term:

$$\frac{\partial T}{\partial t} + \frac{1}{A} \cdot \frac{\partial (u \cdot A \cdot T)}{\partial x} = \frac{1}{A} \cdot \frac{\partial}{\partial x}\left(A \cdot E_L \cdot \frac{\partial T}{\partial x} \right) + \frac{\Phi_n}{\rho_l \cdot C_p \cdot V} \qquad \textbf{(1)}$$

Heat flux. The net heat flux, Φ_n, is a sum of the components accounting for solar radiation, atmospheric radiation, conduction and convection, evaporation, aeration, mechanical energy from mixing, and biological processes, described as:

$$\Phi_n = \Phi_{sr} - \Phi_{ar} - \Phi_c - \Phi_e - \Phi_a + \Phi_m + \Phi_{bp} \qquad \textbf{(2)}$$

The flux expressions originate from two models reported by Sedory and Stenstrom (1995) and by Scherfig *et al.* (1996) with two exceptions for Φ_{bp} and Φ_{sr}. Solar radiation, Φ_{sr}, is not computed, but is measured at a meteorological station. The equation for the biological processes heat exchange, Φ_{bp}, is adopted from la Cour Jansen *et al.* (1992), who computed heat released during exothermic biological processes, such as carbon oxidation, nitrification and denitrification based on Gibb's free energy terms. This modification appears to be crucial for advanced wastewater treatment systems with nitrogen removal. The previous well-known temperature models (Sedory and Stenstrom, 1995; Scherfig *et al.*, 1996) used the equation based only on the organic substrate removal, which did not account for the impact of important biological processes (i.e. nitrification and denitrification).

The heat flux components are defined as follows:

- ***Net short-wave (solar) radiation, Φ_{sr}***
  Φ_{sr} is a direct measurement from a meteorological station.
- ***Net long-wave (atmospheric) radiation, Φ_{ar}***
  The net long-wave radiation, Φ_{ar}, is computed as the difference between incoming and back radiation based on Stefan-Boltzman's law:
  $$\Phi_{ar} = \left[\varepsilon_{ar} \cdot \sigma \cdot T^{*4} - (1 - \lambda_{ar}) \cdot \sigma \cdot T_a^{*4} \cdot \beta_{ar}\right] \cdot A_S \qquad \textbf{(3)}$$
- ***Conduction and convection, Φ_c***
  Surface convection and conduction, Φ_c, is a function of wind velocity and the temperature difference between the mixed liquor in the reactor and air above it:
  $$\Phi_c = \rho_a \cdot C_{p,a} \cdot h_v \cdot A_S \cdot (T - T_a) \qquad \textbf{(4)}$$
  where,
  $$h_v = 392 \cdot A_S^{-0.05} \cdot u_w \qquad \textbf{(5)}$$
- ***Evaporation, Φ_e***
  Evaporation, Φ_e, is a function of wind velocity, relative humidity and the temperature difference between the mixed liquor in the reactor and air above it:
  $$\Phi_{ev} = \left[1.145 \cdot 10^6 \cdot \left(1 - \frac{Rh}{100}\right) + 6.86 \cdot 10^4 \cdot (T - T_a)\right] \cdot e^{0.0604 \cdot T_a} \cdot u_w \cdot A_S^{0.95} \qquad \textbf{(6)}$$
- ***Aeration, Φ_a – only for aeration basin***
  Heat loss due to aeration, consists of two components - sensible loss and latent loss:
  $$\Phi_a = \Phi_{as} + \Phi_{al} \qquad \textbf{(7)}$$
  where,
  $$\Phi_{as} = \rho_a \cdot C_{p,a} \cdot Q_A \cdot (T - T_a) \qquad \textbf{(8)}$$
  $$\Phi_{al} = \frac{M_w \cdot Q_A \cdot \phi_1}{R} \cdot \left\{\frac{e_w \cdot [Rh + h_f \cdot (1 - Rh)]}{(T + 273)} - \frac{e_a \cdot Rh}{(T_a + 273)}\right\} \qquad \textbf{(9)}$$
- ***Mechanical energy, Φ_m– only for aeration basin***
  Heat is generated during the process of compression, and the portion added to the reactor is represented by the blower inefficiency:

$$\Phi_m = P \cdot (1 - \eta_e) \quad \textbf{(10)}$$

- ***Biological processes, Φ_{bp}– only for aeration basin and secondary clarifier***
  Heat released during exothermic biological processes, such as carbon oxidation, nitrification and denitrification is computed based on Gibb's free energy terms:

$$\Phi_{bp} = -\left(\Delta G_1 \cdot \frac{\Delta S}{32} + \Delta G_2 \cdot \frac{8 \cdot S_{ND,in}}{14} + \Delta G_3 \cdot \frac{5 \cdot 0.8 \cdot S_{ND,in}}{14} \right) \cdot Q \quad \textbf{(11)}$$

Dispersion. The value of the longitudinal dispersion coefficient, E_L, can be estimated from empirical formulas (Makinia, 1998) or from tracer studies. Details of one experimental and analysis procedure can be found in Makinia and Wells (2000).

Numerical solution. The following explicit finite difference approximation was used to solve the 1-D advection-dispersion equation with the net heat flux in the reaction term described by Equation 2, as follows:

$$V_i \cdot \frac{T_i^{n+1} - T_i^n}{\Delta t} = u_{i-1}^n \cdot A_{i-1} \cdot T_{i-1}^n - u_i^n \cdot A_i \cdot T_i^n + A_{i+1/2} \cdot E_{L,i+1/2} \cdot \frac{T_{i+1}^n - T_i^n}{\Delta x_{i+1/2}} - A_{i-1/2} \cdot E_{L,i-1/2} \cdot \frac{T_i^n - T_{i-1}^n}{\Delta x_{i-1/2}} + \frac{\Phi_{n,i}^n}{\rho_l \cdot C_p} \quad \textbf{(12)}$$

Appendix B: Symbols and used in temperature model

Table 1. List of symbols (other symbols are shown in Table 2).

A	Cross-sectional area at inlet to the control volume	L^2
C_p	Specific heat of water at constant pressure	$L^2T^{-2}deg^{-1}$
E_L	Longitudinal dispersion coefficient	L^2T^{-1}
f_H	Proportionality factor containing all of the heat transfer characteristics	LT^{-1}
H	Reactor depth	L
i	Subscript denoting cell number in reactor	
n	Superscript denoting time level	
Q_{tot}	Total flowrate through activated sludge reactor	L^3T^{-1}
T*	Absolute temperature	deg
T_{in}	Temperature of wastewater in inlet to reactor	deg
t	Time	T
$\bar{t}$	Theoretical hydraulic retention time	T
u	Flow velocity in reactor	LT^{-1}
V	Reactor volume	L^3
x	Distance along reactor axis	L

Φ_a	Aeration heat transfer flux	ML^2T^{-3}
Φ_{al}	Evaporative (latent) heat transfer associated with aeration flux	ML^2T^{-3}
Φ_{as}	Convective (sensible) heat transfer associated with aeration flux	ML^2T^{-3}
Φ_{bp}	Biological processes heat exchange flux	ML^2T^{-3}
Φ_{ar}	Long-wave (atmospheric) radiation flux	ML^2T^{-3}
Φ_c	Surface convection and conduction flux	ML^2T^{-3}
Φ_e	Surface evaporation flux	ML^2T^{-3}
Φ_m	Mechanical power heat exchange flux	ML^2T^{-3}
Φ_n	Net heat exchange flux	ML^2T^{-3}
Φ_{sr}	Short-wave (solar) radiation flux	ML^2T^{-3}
ρ_l	Liquid density in reactor	ML^{-3}

Table 2. Parameters occurring in the heat flux components for the complete model (equations 3-12)

Symbol	Definition	Dimension	Actual unit	Value	Reference
Meteorological data					
Rh	Relative humidity fraction	dimensionless	-	variable	measurements
T_a	Air temperature	deg	K	variable	measurements
u_w	Wind velocity	LT^{-1}	m/s	variable	measurements
β_{ar}	Atmospheric radiation factor	dimensionless	-	0.95	literature
Process data					
A_S	Surface area of reactor	L^2	m^2		design data
P	Power of aerator/compressor	ML^2T^{-2}	W		manufacturer's data
Q	Influent flowrate	L^3T^{-1}	m^3/d	variable	measurements
Q_A	Air flowrate	L^3T^{-1}	m^3/d	variable	measurements
$S_{ND,in}$	Soluble biodegradable organic nitrogen concentration in inlet to reactor	$M(N)L^{-3}$	kg/m^3	variable	measurements
T	Temperature of wastewater in reactor	deg	K	variable	measurements
ΔS	Mass of substrate (as COD) removed per day	MT^{-1}	kg/m^3	variable	measurements
η_e	Efficiency of aerator/compressor	dimensionless	-	0.4	manufacturer's data
Physical properties					
$C_{p,a}$	Specific heat of air at constant pressure	$L^2T^{-2}deg^{-1}$	J/(kg K)	1014	literature
e_a	Vapor pressure of air at air	$ML^{-1}T^{-2}$	Pa	variable	literature

	temperature				
e_w	Vapor pressure of water at reactor temperature	$ML^{-1}T^{-2}$	Pa	variable	literature
h_f	Exit air humidity factor	dimensionless	-	1	literature
h_v	Convective (vapor) transfer coefficient	LT^{-1}	m/s	variable	calculated
M_w	molecular weight of water	$Mmole^{-1}$	g/mole	18	literature
R	Universal gas constant	$ML^2T^{-2}deg^{-1} mole^{-1}$	J/(kmole K)	8314.7	literature
ΔG_1	Gibb's free energy for aerobic respiration	$ML^2T^{-2}\ e^{-1}$	kJ/e	-110	literature
ΔG_2	Gibb's free energy for nitrification	$ML^2T^{-2}\ e^{-1}$	kJ/e	-43	literature
ΔG_3	Gibb's free energy for denitrification	$ML^2T^{-2}\ e^{-1}$	kJ/e	-104	literature
ε_{ar}	Water surface emissivity	dimensionless	-	0.97	literature
ϕ_l	Latent heat of evaporation	L^2T^{-2}	J/g	2263	literature
λ_{ar}	Water surface reflectivity	dimensionless		0.03	literature
ρ_a	Air density	ML^{-3}	kg/m^3	1.2	literature
σ	Stefan Boltzman constant	$MT^{-3}deg^{-4}$	$W/(m^2\ K^4)$	$5.67\ 10^{-8}$	literature