Temperature Modeling in Activated Sludge Systems: A Case Study

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ABSTRACT: A model of temperature dynamics was developed as part of a general model of activated-sludge reactors. Transport of heat was described by the one-dimensional, advection-dispersion equation, with a source term based on a theoretical heat balance over the reactor. The model was compared to several reference models, including a tanks-in-series model and the dispersion model with heat components neglecting biochemical-energy inputs and other activated-sludge, heat-balance terms. All the models were tested under steady-state and dynamic conditions at a full-scale facility, the Rock Creek wastewater treatment plant in Hillsboro, Oregon, using meteorological data from a station located 16 km from the plant. The dispersion model and tanks-in-series model matched in situ temperature data with absolute-mean errors less than 0.1°C. Neglecting biochemical-heat-energy inputs in the activated-sludge reactor underestimated temperatures by up to 0.5°C. The biochemical-heat-energy inputs accounted for 30 to 40% of the total heat flux throughout the year. *Water Environ. Res.,* **77,** 000 (2005).

KEYWORDS: activated sludge, heat balance, hydraulics, modeling, temperature dynamics, wastewater treatment.

Introduction

An activated-sludge reactor is a complex physical-chemical-biological system with internal interactions between process variables and dynamic changes in influent wastewater flowrate, concentration, and composition. Existing mathematical models of activated-sludge systems focus primarily on the microbiology and often assume constant temperature.

Temperature dynamics affect changes in the microbial activity and physiochemical properties of the mixed liquor in the activated-sludge system. A diurnal temperature difference between inlet and outlet typically varies between 0.5 and 1°C; however, in some parts of the world, activated-sludge reactors are subjected to significant winter cooling and summer heating. The development of accurate temperature models of wastewater-treatment-plant processes is important, not only for modeling the link between temperature and biological kinetics (especially nitrification), but also to understand heat losses and gains through a treatment plant. For example, in many states, the effluent temperature from wastewater treatment plants (WWTPs) is being scrutinized as an excess heat load to rivers during the winter. Accurate modeling of temperature dynamics of unit processes is an important aspect of understanding how that excess heat load can be reduced.

The aim of this research is to study the effect of potential improvements that can be made to the existing temperature models for activated-sludge systems. The newly developed model, which is part of a general model of activated-sludge reactors (Makinia and Wells, 2000), is compared with some reference models using available field data, both short-term and long-term, from a full-scale facility. Furthermore, the contribution of specific heat components on the temperature-model predictions is also evaluated.

Background

Eckenfelder (1966) proposed the following simple equation for estimating the equilibrium temperature in aerated lagoons using surface-aeration equipment:

$$\frac{\bar{t}}{H} = \frac{T_{in} - T}{f_H \cdot (T - T_a)} \tag{1}$$

Where

f_H = proportionality factor containing all of the heat-transfer characteristics (LT^{-1}),
H = reactor depth (L),
$\bar{t}$ = theoretical hydraulic-retention time (T),
T = temperature in reactor (deg),
T_{in} = temperature of wastewater in inlet to reactor (deg), and
T_a = ambient temperature (deg).

The coefficient f_H combines all of the heat-transfer characteristics, including the heat-transfer coefficients, surface-area increase from aeration equipment, and wind and humidity effects. An approximate value of f_H was 27 m/d (90 ft/day) for most aerated lagoons. Another simple equation for aerated lagoons was recently proposed by Grady et al. (1999).

Ford et al. (1972) developed an empirical method for estimating temperature changes in activated-sludge basins equipped with mechanical-surface aerators. This technique included calculation of heat losses from aerator spray as a function of the differential enthalpy of the airflow into the basin.

Novotny and Krenkel (1973) presented a comprehensive steady-state model for calculating the equilibrium temperature in aeration basins based on theoretical energy balances using a cooling-pond approach. The model included four energy balance terms: (1) short-wave (solar) radiation, (2) long-wave (atmospheric) radiation, (3) evaporation, and (4) convection. Argaman and Adams (1977) extended Novotny and Krenkel's model by adding the heat gains from mechanical energy input and biochemical reactions and the heat loss through the basin walls. Talati and Stenstrom (1990) integrated the best parts of the previous models and improved the accuracy of temperature prediction to ±1.2°C and reduced the amount of site-specific information needed. Sedory and Stenstrom (1995) used the equations from the model by Talati and Stenstrom (with slight changes with respect to solar radiation and biochemical-process energy) and developed a dynamic model to predict activated-sludge-basin temperature. In concurrent studies, Bround and Scherfig (1994) and Scherfig et al. (1996) used Argaman and Adams' equations, except energy exchange from aeration, which was adapted from Talati and Stenstrom (1990). Both dynamic models were able to predict the hourly temperature changes in activated-sludge basins within ±0.5°C.

Table 1—Typical range of contributions temperature changes in treatment plants (la Cour Jansen et al., 1992).

Energy transfer phenomena	Temperature change (°C/day)
Significant energy contributions:	
Short-wave radiation (increase)	0.5 to 2.5
Long-wave radiation (decrease)	0.5 to 1.0
Sensible heat (decrease/increase)	0.5 to 3.5
Evaporation (decrease)	0.5 to 2.5
Process energy (increase)	0.5 to 2.0
Insignificant energy contributions:	
Mechanical energy	<0.1
Geothermal energy (decrease/increase)	<0.05
Precipitation (rain/snow at surface) (decrease/increase)	<0.2

Wells (1990) modeled the temperature regime of a typical WWTP using numerical and analytical techniques, but did not account for mechanical- or biochemical-energy inputs in the activated-sludge reactor. The results indicated that, under winter conditions, covering the aeration basins would cause a 2°C increase in temperature, whereas increasing the recycle rate from 50 to 100% would decrease exit temperature in the aeration basin by approximately 0.3°C.

La Cour Jansen et al. (1992) developed a steady-state temperature model based on a simple energy balance including the significant energy influences (Table 1) and using the equations from Seicz et al. (1969) and Wilson (1974). Although inlet temperature had the greatest effect on the plant temperature, deep tanks and good protection against wind exposure were shown to be attractive means to avoid low process temperatures during winter periods.

Materials and Methods

Model Development. *Transport Equation.* Transport of energy in the activated-sludge reactor is described by the one-dimensional (assuming complete mixing in cross-section), advection-dispersion equation, with a source term, as follows:

$$\frac{\partial T}{\partial t} + \frac{1}{A}\cdot\frac{\partial(u\cdot A\cdot T)}{\partial x} = \frac{1}{A}\cdot\frac{\partial}{\partial x}\left(A\cdot E_L\cdot\frac{\partial T}{\partial x}\right) + \frac{\Phi_n}{\rho_l\cdot C_p\cdot V} \quad (2)$$

Where

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}),
U = flow velocity in reactor (LT^{-1}),
x = distance along reactor axis (L),
Φ_n = net-heat-exchange flux (ML^2T^{-3}),
ρ_l = liquid density in reactor (ML^{-3}), and
V = reactor volume (L^3).

Expressions used for the net heat exchange Φ_n are described below.

The assumption of complete mixing was commonly used in several studies dealing with transport in activated-sludge reactors (Makinia, 1998). Moreover, preliminary checks of vertical temperature profiles and transverse distribution of tracer concentrations at the end of the activated-sludge reactor at the plant under study supported the validity of this assumption.

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 the following:

$$\Phi_n = \Phi_{sr} - \Phi_{ar} - \Phi_c - \Phi_e - \Phi_a + \Phi_m + \Phi_{bp} \quad (3)$$

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 effect of important biological processes (i.e., nitrification and denitrification).

The heat flux components are defined as follows:

- Net short-wave (solar) radiation, Φ_{sr}. The 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, as follows (Note: Variables in eqs 4 to 12 are defined in Table 2):

$$\Phi_{ar} = \left[\varepsilon_{ar}\cdot\sigma\cdot T^{*4} - (1-\lambda_{ar})\cdot\sigma\cdot T_a^{*4}\cdot\beta_{ar}\right]\cdot A_S \quad (4)$$

- 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, as follows:

$$\Phi_c = \rho_a\cdot C_{p,a}\cdot h_v\cdot A_S\cdot(T - T_a) \quad (5)$$

Where h_v is defined as follows:

$$h_v = 392\cdot A_S^{-0.05}\cdot u_w \quad (6)$$

- 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, as follows:

$$\Phi_{ev} = \left[1.145\cdot10^6\cdot\left(1-\frac{Rh}{100}\right) + 6.86\cdot10^4\cdot(T - T_a)\right]\cdot e^{0.0604\cdot T_a}\cdot u_w\cdot A_S^{0.95} \quad (7)$$

- Aeration, Φ_a. Aeration is heat loss resulting from aeration and consists of two components—sensible loss and latent loss—as follows:

$$\Phi_a = \Phi_{as} + \Phi_{al} \quad (8)$$

Where Φ_{as} is as defined in eq 9 and Φ_{al} is as defined in eq 10.

$$\Phi_{as} = \rho_a\cdot C_{p,a}\cdot Q_A\cdot(T - T_a) \quad (9)$$

$$\Phi_{al} = \frac{M_w\cdot Q_A\cdot\phi_l}{R}\cdot\left\{\frac{e_w\cdot[Rh + h_f\cdot(1-Rh)]}{(T+273)} - \frac{e_a\cdot Rh}{(T_a+273)}\right\} \quad (10)$$

Table 2—Parameters occurring in the heat-flux components for the complete model (eqs 4 to 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	1310.4	Design data
P	Power of aerator/compressor	ML^2T^{-3}	W	$1\ 10^5$	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 chemical-oxygen demand [COD]) removed per day	MT^{-1}	kg/d	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 temperature	$ML^{-1}T^{-2}$	Pa	Variable	Literature
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

- Mechanical energy, Φ_m. Heat is generated during the process of compression, and the portion added to the reactor is represented by the blower inefficiency, as follows:

$$\Phi_m = P \cdot (1 - \eta_e) \tag{11}$$

- Biological processes, Φ_{bp}. Heat released during exothermic biological processes, such as carbon oxidation, nitrification, and denitrification, is computed based on Gibb's free energy terms, as follows:

$$\Phi_{bp} = -\left(\Delta G_1 \cdot \frac{\Delta S}{32} + \Delta G_2 \cdot \frac{8 \cdot S_{ND,in}}{14} + \Delta G_3 \cdot \frac{5 \cdot 0.8 \cdot S_{ND,in}}{14}\right) \cdot Q \tag{12}$$

Dispersion. The value of the longitudinal dispersion coefficient, E_L, can be estimated from empirical formulas (Makinia, 1998) or from tracer studies performed on the activated-sludge reactor studied. Values of the E_L coefficient from dye-tracer experiments were in the range 1100 to 1500 m^2h^{-1} and were estimated by setting a sum of squares of differences between the observed and calculated tracer concentrations to a minimum. Details of the 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 one-dimensional, advection-dispersion equation, with the net heat flux in the reaction term described by eq 2, as follows:

$$V_i \cdot \frac{T_i^{n+1} - T_i^n}{\Delta t} = u_{i-1}^n \cdot A_{i-1} \cdot T_{i-1}^n - u_i^n \cdot A_i \cdot T_i^n + A_{i+1/2} \cdot E_{L,i+1/2} \cdot \frac{T_{i+1}^n - T_i^n}{\Delta x_{i+1/2}} - A_{i-1/2} \cdot E_{L,i-1/2} \cdot \frac{T_i^n - T_{i-1}^n}{\Delta x_{i-1/2}} + \frac{\Phi_{n,i}^n}{\rho_l \cdot C_p} \tag{13}$$

A heat balance upon a grid cell is shown in Figure 1. This one-dimensional dispersion model was termed *DISP.*

Reference Models. *DISP Model without the Biological-Process Term.* It has been hypothesized that energy from biological processes may be a significant heat input to activated-sludge systems. To verify this hypothesis, the original DISP model was modified by removing the biological-process term (Φ_{bp}) from the net heat flux. The new model was termed $DISP_{w/obp}$.

Tanks-in-Series Model. Activated-sludge systems are generally modeled as dynamic tanks-in-series. To compare the effect of flow conditions, a tank-in-series model (TIS) was developed using the same heat-balance equations as in the advection-dispersion model for the net heat flux (eqs 3 to 12), as follows:

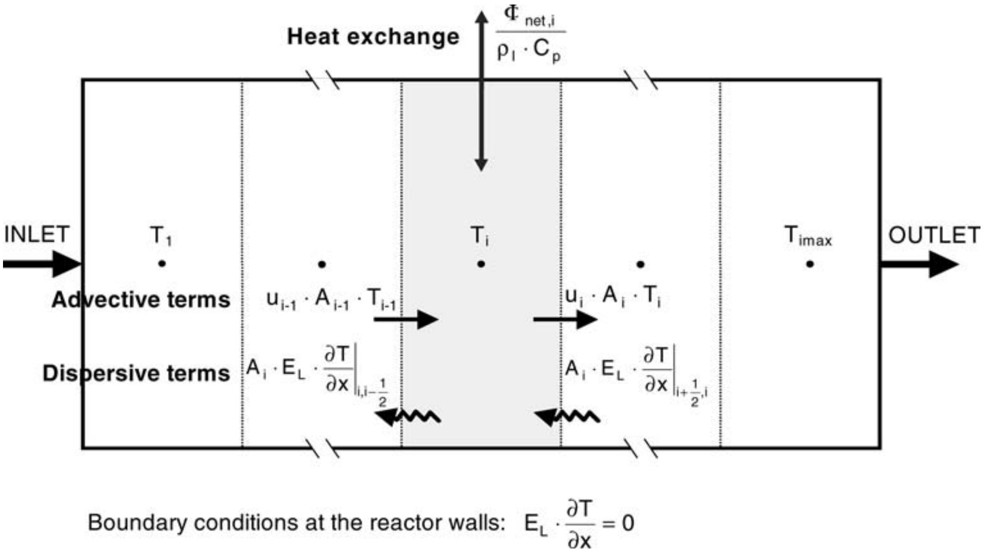

Figure 1—Schematic diagram showing a heat balance over a grid element of an activated-sludge reactor.

$$\frac{dT}{dt} = \left(\frac{Q_i}{V_i}\right) \cdot T_{i-1} - \left(\frac{Q_i}{V_i}\right) \cdot T_i + \frac{\Phi_n}{\rho_l \cdot C_p \cdot V_i} \tag{14}$$

The following explicit scheme was used as a numerical solution:

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = \left(\frac{Q_i}{V_i}\right) \cdot T_{i-1}^n - \left(\frac{Q_i}{V_i}\right) \cdot T_i^n + \frac{\Phi_{n,i}^n}{\rho_l \cdot C_p \cdot V_i} \tag{15}$$

Based on the operating conditions (see Figure 2), five tanks were assumed for the TIS model. More details on this approach can be found elsewhere (Makinia and Wells, 2000).

Heat-Balance Model for Heated Discharges into Natural Systems. Another useful comparison to the heat-flux model developed for the activated-sludge system was a model (termed *CP* for cooling pond) that neglects biochemical-energy inputs and other activated-sludge, heat-balance terms. For this purpose, surface-heat-transfer terms, originally developed for cooling ponds, natural ponds, and lakes, was used as in Adams and Wells (1984). The following equation from Ryan et al. (1974) was used to compute the net-surface-heat flux, Φ_n, in eq 2:

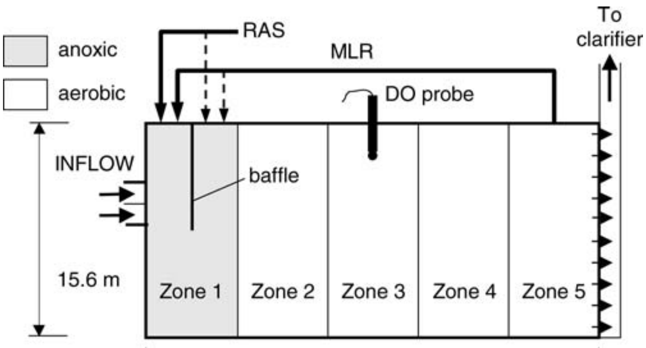

Figure 2—Schematic diagram of aeration basin at the Rock Creek (Makinia and Wells, 1999) (RAS: returned-activated sludge, MLR: mixed-liquor recirculation).

$$\Phi_n[W] = \left\{ \begin{array}{l} 0.94 \cdot \varphi_{sc} \cdot (1 - 0.65 \cdot CC^2) + 5.15 \cdot 10^{-13} \cdot (T_a + 273)^6 \\ \cdot (1 + 0.17 \cdot CC^2) - 5.51 \cdot 10^{-8} \cdot (T + 273)^4 \\ -[2.7 \cdot (T_v - T_{av})^{1/3} + 3.2 \cdot u_w] \cdot (e_{sat} - e_a) \\ \cdot \left[1 + 0.61 \cdot \frac{T - T_a}{e_{sat} - e_a}\right] \end{array} \right\} \cdot A_S \tag{16}$$

Where temperatures are in °C, pressures in mm Hg, radiation in W/m^2, and wind speed in m/s at 2 m measuring height.

$$T_v = \frac{(T + 273)}{\left[1 - 0.378 \cdot \left[\frac{e_{sat}}{p}\right]\right]} \tag{17}$$

$$T_{av} = \frac{(T_a + 273)}{\left[1 - 0.378 \cdot \left[\frac{e_a}{p}\right]\right]} \tag{18}$$

$$e_a = Rh\ 25.4\ \exp\ 17.62\ \frac{9500.8}{T_a + 460} \tag{19}$$

$$e_{sat} = 25.4\ \exp\ 17.62\ \frac{9500.8}{T + 460} \tag{20}$$

Where temperatures are in °C (eqs 17 and 18) or °F (eqs 19 and 20).

Equation 16 was then used for ϕ_n in the numerical solution of eq 2. The parameters occurring in eq 16 are listed in Table 3.

Site Description. The Rock Creek WWTP is located in Hillsboro, Oregon, and discharges to the Tualatin River. The Tualatin River is listed as water-quality-limited for temperature and has had total-maximum-daily loads established for both ammonia and total phosphorus. This river is approximately 20 m wide and 2 m deep at the Rock Creek discharge during the summer low-flow period, when the median flow is approximately 3 m^3/s.

The plant is operated by Unified Sewerage Agency of Washington County, Hillsboro, Oregon, 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.

Table 3—Parameters occurring in the heat-flux components for the cooling-pond model (eq 16).

Symbol	Definition	Dimension	Actual unit	Value	Reference
Meteorological data					
CC	Cloud-cover fraction (0 to 1)	Dimensionless	Fraction	Variable	Measurements
p	Atmospheric pressure	$ML^{-1}T^{-2}$	mm Hg	Assumed constant at 1 atm or 760 mm Hg	Measurements, if available
T_{av}	Virtual air temperature	deg	°C	Variable	Calculations, based on eq 17
T_v	Virtual surface temperature	deg	°C	Variable	Calculations, based on eq 18
u_w	Wind velocity	LT^{-1}	m/s	Variable	Measurements
φ_{sc}	Clear-sky, solar-radiation flux	MT^{-3}	W/m^2	Variable	Measurements
Process data					
A_S	Surface area of reactor	L^2	m^2	1310.4	Design data
T	Temperature of wastewater in reactor	deg	°C	Variable	Measurements
Physical properties					
e_a	Vapor pressure of air at air temperature	$ML^{-1}T^{-2}$	mm	Variable	Calculations, based on eq 19
e_{sat}	Saturated vapor pressure of water at water surface temperature	$ML^{-1}T^{-2}$	mm	Variable	Calculations, based on eq 20

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 subzones (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. Comprehensive research (Makinia, 1998) has been conducted on a selected single reactor (aeration basin 4), which is shown in Figure 2.

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.

Dynamic (Short-Term) Temperature-Simulation Data. Data collected for verification of the temperature model were part of a comprehensive continuous test performed on June 23 to 24, 1997, at the Rock Creek WWTP (Makinia and Wells, 2000). The data used for the temperature study included the following:

- Temperature of incoming wastewater. Automatic readings of the plant-influent temperature, recorded at one-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. Consequently, 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 measured several times in the effluent from each zone (1B to 5) of the reactor. For practical reasons, the temperature could only be measured at the sides of the reactor. During the dynamic experiment, the sampling points were set at the depth of 1.0 m.
- Meteorological parameters required to solve the heat-balance equation. All necessary parameters were available from the Agrimet meteorological station recorded at 15-minute to 1-hour intervals.

Dynamic Steady-State (Long-Term) Temperature Simulation Data. In 1996, temperature was measured once a day at 8:00 a.m. at the following locations: plant influent, primary effluent, secondary effluent, and plant effluent. Secondary treatment contributed most significantly to changes in the liquid temperature. The covered primary clarifiers and tertiary treatment (closed claricones) had negligible temperature changes from inlet to outlet.

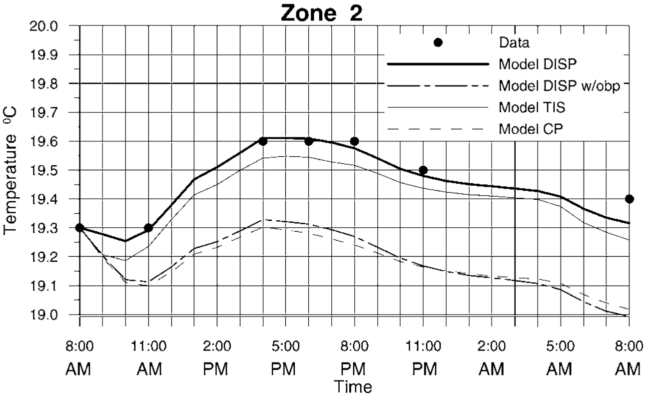

Figure 3—Observed and predicted temperature in effluent from zone 2 of aeration basin 4 during the continuous experiment performed on June 23 to 24, 1997.

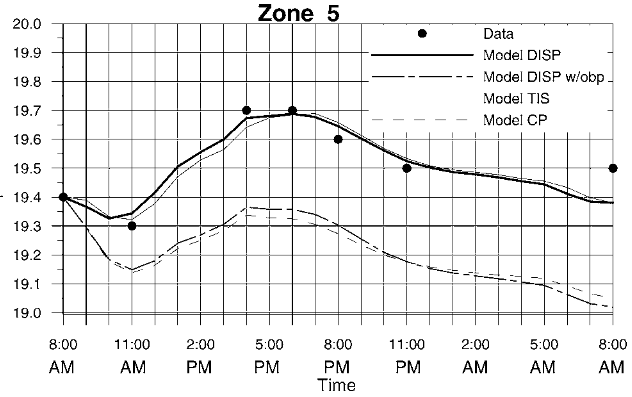

Figure 4—Observed and predicted temperature in effluent from zone 5 of aeration basin 4 during the continuous experiment performed on June 23 to 24, 1997.

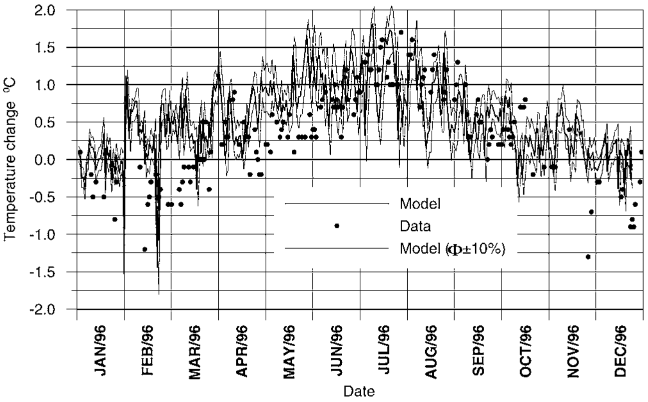

Figure 5—Observed and predicted temperature changes from reactor inlet to reactor exit in aeration basin at the Rock Creek WWTP in 1996.

The temperature gains or losses from the inlet to the outlet for the secondary treatment system were approximately ±1.5°C in 1996.

Solving the heat-balance equation required a certain number of meteorological parameters. Daily average values of air temperature, solar radiation, humidity, dewpoint temperature, and windspeed were available from the Agrimet meteorological station located in Forrest Grove (approximately 16 km from the plant).

Results

Short-Term Simulations. Model-data comparisons were made in each of the five zones shown in Figure 2. Examples of the simulation results in selected points of aeration basin 4 are shown in Figures 3 and 4 for zones 2 and 5, respectively. The differences in the observed and predicted temperatures from two models (DISP and TIS) were small at each sampling point (Makinia and Wells, 1999). This assessment of the model error is even more difficult because the accuracy of the temperature measurements (±0.1°C) is of the same order of magnitude as the model error. While temperature predictions of the TIS and DISP were very similar, predictions of other water-quality parameters (such as dissolved oxygen) were significantly different in both models (Makinia and Wells, 2000).

When the expressions were taken from the $\mathrm{DISP}_{\mathrm{w/obp}}$ and CP models, the predicted temperatures were relatively low in comparison to observations and predictions incorporating processes unique to the activated-sludge process. Moreover, it turned out that the CP model was insensitive to changes in the evaporation model, e.g., the use of Lake Hefner evaporation model (Adams et. al., 1979) caused minor temperature changes (approximately 0.001°C) compared to the Ryan-Harleman evaporation model used in eq 16. These results indicate that factors specific to the activated-sludge process play an important role in the heat budget on the activated-sludge reactor. Average errors for the four tested models are presented in Table 4.

Table 4—Absolute-mean-temperature error* of the model predictions between June 23 and 24, 1997 (No. of observations = 7).

	Model DISP	Model $\mathrm{DISP}_{\mathrm{w/obp}}$	Model TIS	Model CP
Zone	°C	°C	°C	°C
Zone 1B	0.05	0.22	0.05	0.24
Zone 2	0.02	0.26	0.07	0.27
Zone 3	0.04	0.26	0.04	0.27
Zone 4	0.04	0.27	0.04	0.28
Zone 5	0.04	0.28	0.04	0.29

* Absolute-mean error is defined as $\frac{\sum |T_{data} - T_{model}|}{\#\ observations}$.

Long-Term Simulations. To assess the contributions of all heat-flux components, an additional analysis was performed. The temperature model (DISP) was adapted to generate steady-state solutions, understood as the daily-average-temperature changes in aeration basin 4, over the whole year 1996. The model predictions were compared with the observed data, which is shown in Figure 5. The absolute mean error between the observations and predictions was 0.41°C (with a standard deviation of the absolute errors of ±0.34°C). A simple uncertainty analysis revealed that the model predictions were not extremely sensitive (±0.1 to 0.2°C) to changes (±10%) in the net-heat flux (Figure 5). In addition to the prediction capability of the model, a potential contribution to the error originated from comparing temperature predicted by the model on a daily average basis to an instantaneous temperature measurement. It is also apparent that the model predicted temperature better in the summer months than in the winter months. The reason for this could be adopting constant values of many parameters over the year, whereas it is known that some of them can vary in terms of the meteorological conditions and limitations in using meteorological data at a site 16 km from the WWTP. For example, the atmospheric radiation factor β is a function of cloud cover, cloud height, and vapor pressure (Sedory and Stenstrom, 1995). In this study, a relatively high value of this coefficient (0.95) was assumed within the typical range. On the other hand, β can be as low as 0.75 (Talati and Stenstrom, 1990).

Discussion

Based on the predicted values of the temperature changes in aeration basin 4, the monthly average contributions of the single-heat-flux components were estimated (Figure 6). The analysis revealed that biological processes, causing a net-heat gain, are the most important heat-flux contributor. They account for 30 to 40% of the total flux during the whole year. During summer months, the

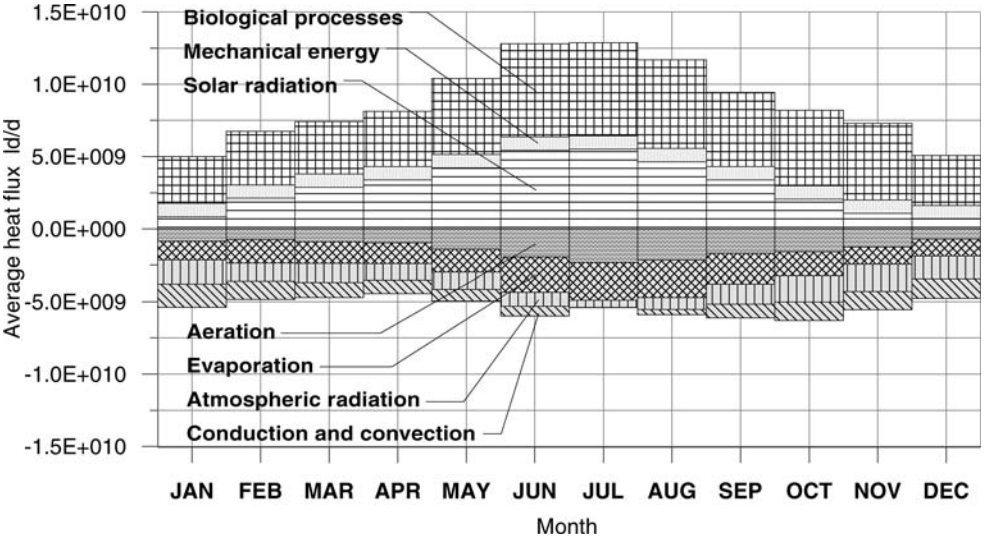

Figure 6—Contributions of the single components to the heat balance for aeration basin 4 determined from the temperature model.

gain from solar radiation (30% of the total flux) is approximately equal to the gain from biological processes, but, during winter months, it becomes a minor component, falling below 8% of the total flux. The heat gain from mechanical energy remains a minor component through the whole year, accounting for 5 to 9% of the total flux.

Atmospheric radiation and conduction/convection are the most important heat-loss components in winter months, accounting for approximately 15% of the total flux. However, during summer months, the contribution of atmospheric radiation and convection/conduction is negligible (less than 3% of the total flux). Unlike these two processes, evaporation and aeration are the major heat losses during summer months (15 and 13% of the total flux, respectively), but play a minor role during winter months (9 and 7%, respectively).

Conclusions

A temperature model using a one-dimensional, advective-dispersion model was developed as a part of a comprehensive model of activated-sludge reactors. The DISP model matched experimental data and the tanks-in-series (TIS) model with the same net-heat-balance term. The average prediction errors during dynamic simulations varied within the range of 0.02 to 0.05°C for the DISP model and 0.04 to 0.07°C for the TIS model. Both ranges remain below the accuracy level of the measuring equipment. However, more considerable prediction errors were obtained (0.24 to 0.29°C) using the advection-dispersion equation as a transport model, with a net-heat balance neglecting biochemical-energy inputs to the reactor.

Using a steady-state temperature model with the advective-dispersive transport for long-term simulations, the average difference between observations and predictions was equal to 0.41°C (±0.34°C). Based on the predicted values, biological processes accounted for 30 to 40% of the total heat flux throughout the year. This result may indicate the need for further research on understanding the thermodynamics of biological processes. The simple equation used for the heat flux of biological processes in the previous temperature models may be applicable only in conventional-activated-sludge systems, but not in biological-nutrient-removal systems.

Nomenclature

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}

*Note: Symbols occurring in eqs 4 to 12 and 16 are listed in Tables 2 and 3, respectively.

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References

Adams, E. E.; Wells, S. A. (1984) Field Measurements on Side Arms of Lake Anna, Virginia. *J. Hydraulic Eng. ASCE,* **110** (6), 773–793.

Adams, E. E.; Harleman, D. R. F.; Jirka, G.; Stolzenbach, K. (1979) Heat Disposal in the Water Environment; Parsons Laboratory, MIT, Department of Civil Engineering: Cambridge, Massachusetts.

Argaman, Y.; Adams Jr., C.E. (1977) Comprehensive Temperature Model for Aerated Biological Systems. *Prog. Water Technol.,* **9,** 397–409.

Bround, S.; Scherfig, J. (1994) Dynamic Temperature Changes in Nutrient Removal Plants. *Water Sci. Technol.,* **30** (2), 205–208.

Eckenfelder, W. W. (1966) *Industrial Water Pollution Control,* 1st ed., McGraw-Hill: New York.

Ford, D. L.; Chih, S. S.; Sobosta, E. C. (1972) Temperature Prediction in Activated Sludge Basins Using Mechanical Screens. *Proceedings of the 27th Industrial Waste Conference*, Purdue University, West Lafayette, Indiana, May, **27,** 587.

Grady, C. P. L.; Daigger, G. T.; Lim, H. C. (1999) *Biological Wastewater Treatment*, 2nd ed.; Marcel-Dekker: New York.

la Cour Jansen, J.; Kristensen, G. H.; Laursen, K. D. (1992) Activated Sludge Nitrification in Temperature Climate. *Water Sci. Technol.,* **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, Oregon.

Makinia, J.; Wells, S. A. (1999) Improvements in Modeling Dissolved Oxygen in Activated Sludge Systems. *Proceedings of the 8th International Association on Water Quality Conference on Design, Operation, and Economics of Large Wastewater Treatment Plants,* Budapest, Hungary, September 6–9; International Association on Water Quality: London, p. 518–525.

Makinia, J.; Wells, S. A. (2000) A General Model of the Activated Sludge Reactor with Dispersive Flow: Model Development and Parameter Estimation. *Water Res.,* **34** (16), 3987–3996.

Novotny, V.; Krenkel, P. A. (1973) Evaporation and Heat Balance in Aerated Basins. *AIChE Symposium Series,* **70** (136), 150–159.

Ryan, P. J.; Harleman, D. R. F.; Stolzenbach, K. D. (1974) Surface Heat Loss from Cooling Ponds. *Water Resour. Res.,* **10** (5), 930–938.

Scherfig, J.; Schleisner, L.; Brond, S.; Kilde, N. (1996) Dynamic Temperature Changes in Wastewater Treatment Plants. *Water Environ. Res.,* **68** (2), 143–151.

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

Seicz, G.; Endrodi, G.; Tajchman, S. (1969) Aerodynamic and Surface Factors in Evaporation. *Water Resour. Res.,* **5** (2), 380–393.

Talati, S. N.; Stenstrom, M. K. (1990) Aeration Basin Heat Loss. *J. Environ. Eng. ASCE,* **116** (1), 70–86.

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

Wilson, E. M. (1974) *Engineering Hydrology.* MacMillan Press. Ltd.: London.