Pulp and Paper: Temperature Modeling in Large Basins

Introduction

Approximately 60+% of wastewater produced by the Pulp and Paper industry is treated using large basins (Aerated Stabilization Basin, ASB). Wastewater from primary clarifier effluent typically enters the secondary treatment basin from a single or multi feed configuration. Surface aerators are typically utilized for aeration and mixing purposes in the basin. Carbon and nitrogen removal occur in the basin as a result of heterotrophic and autotrophic biological reactions in the presence of oxygen. Since biological reactions are directly impacted by temperature, prediction of the rate of change of temperature as a result of heat transfer mechanisms that affect the basin wastewater temperature become important. Due to having larger detention time and surfaces areas compared to activated sludge tanks, aeration ponds are more prone to being affected by heat transfer through the wastewater/air interface. In general, biological reactions taking place in the pond generate heat. Depending on the temperature model, other components of heat transfer can be taken into account.

This factsheet is the result of extensive review of temperature models in the literature. The challenge with compiling information from existing resources is the confusion due to inconsistencies in nomenclature and units. As a result, efforts were made to resolve these issues by providing a summary of two of the most common temperature models with unified nomenclature and units.

The overall heat balance equation is shown below (Equation 1). For dynamic simulation, a numerical integration technique can be used to simulate the rate of change of temperature as a result of varying inputs. When input variables are constant, steady-state solution is reached and the right-hand side of Equation 1 becomes zero.

$$\Sigma H + \rho_w c_{pw}\left[\sum_{i=1}^{n}\left(Q_{inf,i}T_{inf,i} - Q_{eff}T_w\right)\right] = V\rho_w c_{pw}\frac{dT_w}{dt} \quad \textbf{(1)}$$

Energy balance components for the simple and complete models are illustrated schematically in Table 1 (pg. 2). As can be easily seen, the number of inputs required for the complete model is significant.

Simple Temperature Model

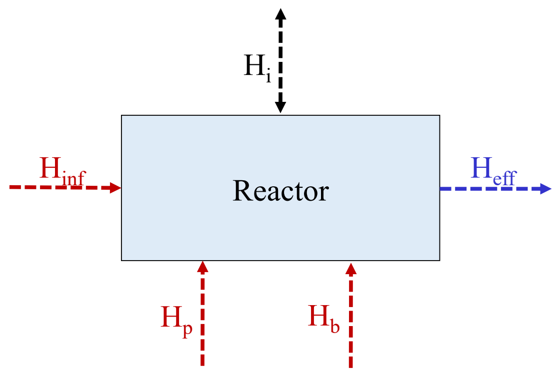
In this model (Gillot and Vanrolleghem 2003, van der Graaf 1976, Hydromantis 2015), four heat transfer parameters are considered. The parameter nomenclature is consistent with the complete model presented next. The strength of the simple model is that it requires very little input data and can be used in most applications with reasonable accuracy as it focuses on the most significant heat transfer mechanisms and neglects others.

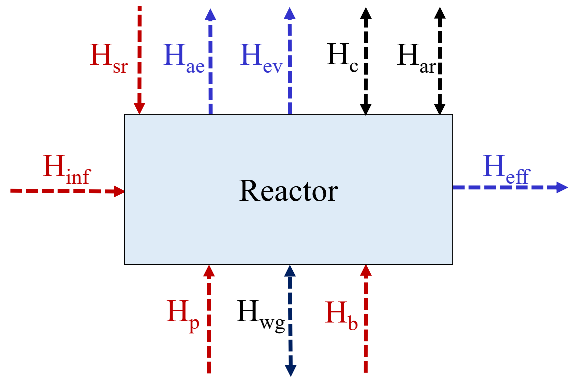
Table 2: Simple Temperature and Model Equations

Term	Equation	
H_p	$s\eta NP_{ae}$	**(4)**
H_b	$-(H_{ou}r_{0,bio.} + H_{denit}r_{denit.} + H_{nit.}r_{nit.})$	**(5)**
H_{wg}	$U_{wg}A_{wg}(T_w - T_g)$	**(6)**
H_i	Surface aeration: $11.4NP_{ae}A_b(T_a-T_w)$ Diffused aeration: $25A_b(T_a-T_w)$	**(7)**

Table 1: Energy Balance Components for the Simple and Complete Temperature Models

Simple	Complete
$\Sigma H = H_p + H_b + H_{wg} + H_i$ **(2)**	$\Sigma H = H_p + H_b + H_{wg} + H_{sr} + H_{ar} + H_{ev} + H_c + H_{ae}$ **(3)**





Parameter	Description	Value	Unit
ΣH	Summation of heat terms	Variable	J/d
H_{inf}	Heat transfer due to influent flow to the system	Variable	J/d
H_{eff}	Heat transfer due to effluent flow leaving the system	Variable	J/d
H_p	Heat transfer rate due to aeration power	Variable	J/d
H_b	Heat transfer rate due to biological reaction	Variable	J/d
H_i	Heat transfer rate due to exchange through air/liquid interface	Variable	J/d
H_{wg}	Heat transfer rate through basin walls and ground	Variable	J/d
H_{sr}	Heat transfer rate due to solar radiation	Variable	J/d
H_{ar}	Heat transfer rate due atmospheric radiation	Variable	J/d
H_{ev}	Heat transfer rate due to evaporation	Variable	J/d
H_c	Heat transfer rate due to surface convection	Variable	J/d
H_{ae}	Heat transfer rate due to aeration	Variable	J/d

Complete Temperature Model

Additional heat transfer terms included in the complete temperature model are solar radiation, atmospheric radiation, and evaporation. The aeration model is an extension of the simple model equation. The advantage of the complete model is that it includes parameters for all heat transfer mechanisms. The downside is that more input information must be either known or assumed. In most cases, assumed values include higher potential error.

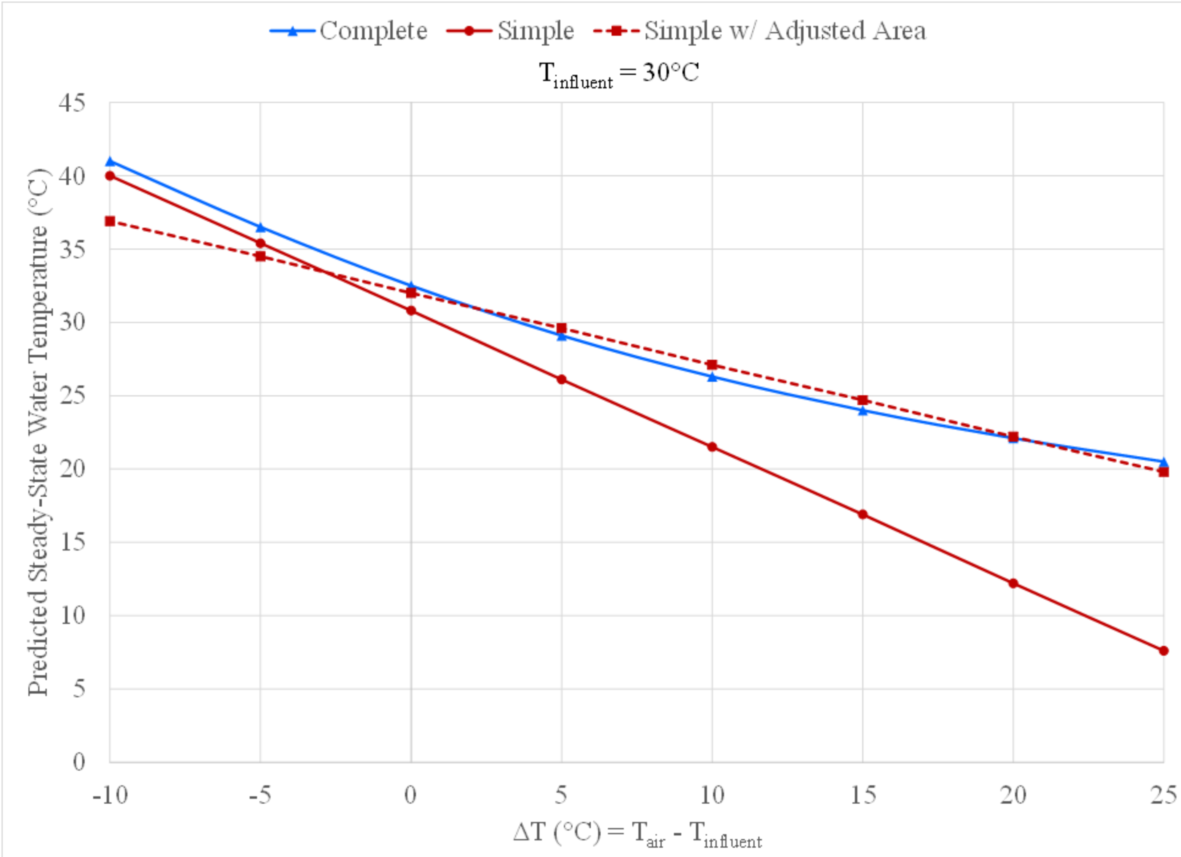
Comparison of Simple and Complete Models

The simple and complete temperature models were used in a recent project aimed at minimizing heat loss in an activated sludge wastewater treatment system in a cold climate. In this case, the complete temperature model produced reasonable results compared to actual field temperature measurements while simple model predicted significantly lower than observed equilibrium temperatures. The original simple model proposed by van der Graaf, takes into account the total area of the aeration basin (Ab) to calculate aeration heat transfer term (Hi), which neglects the fact that the surface area relevant to surface aeration heat exchange is in reality an aerator's zone of influence in terms of creating a splash zone for heat transfer between water droplets and air. In other words, as the number of surface aerators is increased for a given basin surface area (Ab) , the total aeration heat transfer surface area approaches that of the basin surface area assuming that the zones of influence do not disturb one another. To test this hypothesis, Equation 7 was adjusted in order to take into account the total zone of influence area (N*AZOI) rather than total basin area (Ab). Surface aeration zone of influence radius was set to 50 ft (15.24 m) based on aerial photo of the operational surface aerators in the system. Figure 1 (pg. 4) shows the comparison of results for simple, simple with adjusted aeration area, and complete temperature models. The influent temperature was set to 30°C and the effect of the difference in ambient air and influent temperature was investigated. According to the results, the simple model with adjusted aeration area produced results closer to those predicted by the complete temperature model. The need for this adjustment in the Simple model is more pronounced as the absolute difference between air and influent temperature increases.

Table 3: Complete Temperature Model Equations

Term	Equation
Solar Radiation	$H_{sr} = H_{sr,o}(1 - 0.0071C_c^2)A_b$ **(8)** Thackson and Parker 1972: $H_{sr,o} = 4.18 * \left[a - b * \sin\left(\frac{2\pi d}{366} + c\right)\right]$ **(9)** $a = 95.1892 - 0.3591 * k - 8.4537 * 10^{-3} * k^2$ $b = -6.2484 + 1.6645 * k - 1.1648 * 10^{-2} * k^2$ $c = 1.4451 + 1.434 * 10^{-2} * k - 1.745 * 10^{-4} * k^2$ Sedory and Stenstrom 1995: $H_{sr,o} = 6.42 \times 10^{-5}(-0.06401 + 1.3341 * alt + 0.2008 * alt^2 - 0.0043 * alt^3 + 3.79e^{-5} * alt^4 1.37e^{-7} * alt^5)$ **(10)**
Atmospheric Radiation	Novotny and Krenkel 1973, Deas and Lowney 2000: $H_{ar} = A_b\sigma[(1-\lambda)\beta(T_a + 273.15)^4 - \varepsilon(T_w + 273.15)^4]$ **(11)** Argaman and Adams 1977: $H_{ar} = 4.18 \times 10^4 A_b[695(1-\beta) + 10.18(T_w - T_a) + 10.18(1-\beta)T_a]$ **(12)** Atmospheric radiation includes long-wave atmospheric and water surface back-radiation balances. Atmospheric radiation factor (β) is a function of many variables (Anderson 1988) such as air moisture content, and concentrations of ozone and carbon dioxide. The effect of vapor pressure also decreases as the cloud cover increases. It was also noticed that the atmospheric radiation is an inverse function of the height of cloud for a given cloud amount. Albedo ("whiteness" in Latin) of the water surface (λ) is the fraction of incident radiation that is reflected. The non-reflected incident radiation fraction (1-λ) is absorbed and causes an increases in water temperature A water body also emits long-wave radiation (McCutcheon). Clouds and particles in the atmosphere (such as vapor) increase emissivity (ε).
Evaporation	Argaman and Adams 1977: $H_{ev} = -4.18[1.145 \times 10^6(1 - r_h) + 6.86 \times 10^4(T_w - T_a)]e^{0.0604}T_a u_w A^{0.95}$ **(13)** Harbeck (1958, 1962): (for reservoirs up to about 12,140 hectares based on Lake Mead study) $E = 2.91 \times 10^{-6}A_b^{-0.05}u_w(e_{s,w} - e_a)$ **(14)** The saturation vapor pressure (N/m^2), $e_s(T)$, is the highest pressure of water vapor at a given temperature (T, °C) that can exist in equilibrium with a plan, free water surface (Deas and Lowney 2000): $e_s(T) = 610.8e^{\left(\frac{17.27*T}{T+273.15}\right)}$ **(15)**
Convection	Novotney and Krenkel 1973: $H_c = \rho_a c_{pa}(392A_b^{0.95})(u_w - u_s) * (T_w - T_a)$ **(16)** Argaman and Adams 1977: $H_c = 4.93 \times 10^5 u_w A_b^{0.95}(T_w - T_a)$ **(17)** The difference in temperature between air and water surface is the driving force for surface convection heat transfer (Talati and Stenstrom 1990).
Aeration	Argaman and Adams 1977: $H_{ae} = 4.18 \times 4.32 \times 10^4 NFu_w[300(T_w - T_a) + 2{,}920e^{0.0604T_a}(1 - r_h) + 175e^{0.0604T_a}(T_w - T_a)]$ (18) For surface aeration, assuming contact air is saturated with water vapor and is in thermal equilibrium with water, replace NFu_w with $2Q_a$ (Novotny and Krenkel 1973, Argaman and Adams 1977). Diffused aeration (Talati and Stenstrom 1990): $H_{ae} = (sQ_a)\rho_a c_{pa}(T_w - T_a)A_b + 4914.6Q_a s\left\{\frac{e_w[r_h + h_f(1 - r_h)]}{T_w + 273} - \frac{e_a r_h}{T_a + 273}\right\}$ **(19)** Surface aeration (Talati and Stenstrom 1990): $H_{ae} = (392NF^{-0.05}u_w)s\rho_a c_{pa}(T_w - T_a)A_b + 4914.6NFu_w s\left\{\frac{e_w[r_h + h_f(1 - r_h)]}{T_w + 273} - \frac{e_a r_h}{T_a + 273}\right\}$ **(20)** Sensible heat transfer occurs due to contact (between air and water) and depends on the temperature difference as the driving force. Furthermore, a water-phase change can occur due to evaporation and is dependent on the relative humidity of air. Sensible heat transfer results in temperature change while no phase change occurs. On the other hand, no temperature change occurs as a result of latent heat transfer but a change in water phase takes place (liquid to vapor or vice versa). In general, heat loss due to aeration is dependent on the type of aeration (surface or diffused). As a result of greater exposure of water to air, surface aeration heat loss is typically higher than that due to diffused aeration (Talati 1988).

Figure 1: Comparison of simple, simple with adjusted aeration area, and complete temperature models.



Conclusions

As with any modeling task, the model must be selected at the appropriate level of sophistication to provide the required results; all while balancing the amount of time and resources available. Engineering judgement is advocated for here. The tendency is to use the more complex model since more is better right? The problem with this tendency is that it is usually coupled with a lack of detailed input information needed to depict all of the parameters accurately. As a result, the input values selected for the complex model could be based on potentially erroneous assumptions. Garbage in, garbage out.

The simple temperature model summarized in this paper is typically a good candidate for modeling activated sludge tanks and aeration basins with reasonably small temperature differences of less than 20°C ($\Delta T<20$ °C) between influent and air temperatures, and where the surface aeration is influencing the majority of the surface area, i.e., not much open space in the basin. Exceeding either condition without an appropriate adjustment, can result in an inaccurate picture of temperature variations in the basin. As a result, the first task a modeler should consider is to determine the trade-off between accuracy required and time available to develop accurate, representative input parameters. While more complex models can provide better prediction power, the additional data collection and modeling evaluation time can be expensive.

Table 4: Nomenclature

Parameter	Description	Value	Unit
A_b	Basin surface area	Variable	m^2
alt	Solar altitude	Variable	°
A_{wg}	Wall and ground surface area in contact with wastewater	Variable	m^2
A_{ZOI}	Zone of influence per surface aerator	Variable	m^2
C_c	Cloud cover (0-10); clear: 0, Scattered: 3, Broken: 7.5, Overcast: 10	Variable	-
c_{pa}	Air specific heat	1,050	J/(kg.K)
c_{pw}	Water specific heat	4,187	J/(kg.K)
d	Day number	1-365	-
E	Evaporation rate	Variable	m/d
e_a	Vapor pressure at air temperature	Variable	N/m^2
$e_{s,a}$	Saturation water vapor pressure at air temperature	Variable	N/m^2
$e_{s,w}$	Saturation water vapor pressure at water surface temperature	Variable	N/m^2
e_w	Vapor pressure at water temperature	Variable	N/m^2
F	Surface aerator vertical spray area (each)	Variable	m^2
$H_{denit.}$	Heat generation due to denitrification	32,000	$J/gNO_{3,N}$
$H_{nit.}$	Heat generation due nitrification	25,000	$J/gNH_{3,N}$
H_{ou}	Heat generation due biological oxygen removal	13,895	J/gO_2
$H_{sr,o}$	Average daily absorbed solar radiation for clear sky conditions	Variable	$J/(m^2.d)$
k	Site latitude	Variable	°
N	Number of aerators	Variable	-
P_{ae}	Power per aerator	Variable	W
Q_a	Total aeration air flowrate	Variable	m^3/s
Q_{eff}	Basin effluent flowrate = $\sum_{i=1}^{n} Q_{inf,i}$	Variable	m^3/d
$Q_{inf,i}$	Influent steam i wastewater flowrate	Variable	m^3/d
r_{denit}	Denitrification rate	Variable	$g/(m^3.d)$
r_h	Air relative humidity	Variable	decimal
$r_{nit.}$	Nitrification rate	Variable	$g/(m^3.d)$
$r_{O,bio}$	Oxygen consumption rate due to biological reaction	Variable	$g/(m^3.d)$
s	Conversion factor	86,400	sec/day
T_a	Air temperature above water surface	Variable	°C
T_g	Ground temperature in contact with wastewater	Variable	°C
T_{inf}	Influent wastewater temperature	Variable	°C
T_w	Wastewater temperature in the basin	Variable	°C
u_s	Water surface velocity in the wind direction	Variable	m/s
u_w	Wind velocity	Variable	m/s
U_{wg}	Wall and ground interface heat transfer coefficient	Variable	$W/(m^2.°C)$
V	Basin volume	Variable	m^3
β	Atmospheric radiation factor (range: 0.75-0.95)	0.87	-
ε	Water surface emissivity	0.97	-
η	Efficiency factor	Variable	%
λ	Fraction of incident radiation reflected by water surface	0.03	-
ρ_a	Air density = $1.293*273/(T_a+273)$	Variable	kg/m^3
ρ_w	Water density	998	kg/m^3
σ	Stefan-Boltzmann constant	4.9E-3	$J/(d.m^2.K^4)$

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Acknowledgments

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