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# Equilibrium temperature in aerated basins—comparison of two prediction models

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## Abstract

This note presents and compares two models to predict the equilibrium temperature in aerated basins. They differ by their degree of complexity and therefore by the input data they require. Both models were able to estimate the temperature of an industrial aerated lagoon, the more complex model giving, in addition, a complete breakdown of the heat exchanges.

*Keywords:* Activated sludge; Equilibrium temperature; Model; Thermal balance; Wastewater

## 1. Introduction

In biological wastewater treatment processes, operating temperature is highly important as it significantly influences treatment performance, e.g. by increasing pollutant conversion rates typically by a factor when the temperature increases with 10 degrees. Several models have been developed to predict this process temperature: (i) during the design phase of a project [1,2] or (ii) during operation [3–5]. Even dynamic temperature changes in tanks have been successfully modelled [6–8]. These models incorporate the different heat gains/losses over the basins. They however require a large number of input data (meteorological and operating conditions), which are not always easy to collect especially at the design stage of a plant.

On the other hand, few authors developed more simple formulae [9,10]. Among them, van der Graaf [11] proposed a simple, semi-empirical model to evaluate aeration tank temperature, which requires only little data.

The objective of this technical note is to compare the simple model proposed by van der Graaf [11] with a rather complete model developed on the basis of the work by Talati and Stenstrom (1991). Both models are described and they are compared while estimating the equilibrium temperature of an aerated lagoon treating industrial wastewater in the North of France. A comparison of the heat contributions of different processes is made as well.

## 2. Material and methods

### 2.1. Heat balance

The equations presented herein have been developed for a completely mixed basin under steady state conditions. The completely mixed hypothesis supposes that the water temperature is uniform over the basin, and equals the outlet temperature. The energy balance over the reactor implies that the net heat exchange (Qt) equals the enthalpy change between the influent and the effluent streams ($\Delta H$). The latter is written as

$$\Delta H + \rho_w c_{pw} Q_w (T_i - T_w) = 0, \qquad (1)$$

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where $\rho_w$ is the density of water, kg/m$^3$; $c_{pw}$ the specific heat of water, J/kg/K; $Q_w$ the wastewater flow rate, m$^3$/s; $T_i$ the influent temperature, K; and $T_w$ the water temperature, K.

The two models presented differ in the terms they include to calculate the net heat exchange.

### 2.1.1. *Simple model: van der Graaf [11]*

Fig. 1 gives an overview of the heat exchange terms considered in the van der Graaf's model.

The net heat exchange equals (see Fig. 1 for the separate terms and Table 1 for the underlying relationships)

$$\Delta H = \mathrm{Hp} + \mathrm{Hb} - \mathrm{Hi} - \mathrm{Htw}. \tag{2}$$

### 2.1.2. *Complete model: Talati and Stenstrom [5]*

Fig. 2 gives an overview of the heat exchange terms considered in the complete model.

The net heat exchange equals (see Fig. 2 for the separate terms and Table 2 for the underlying

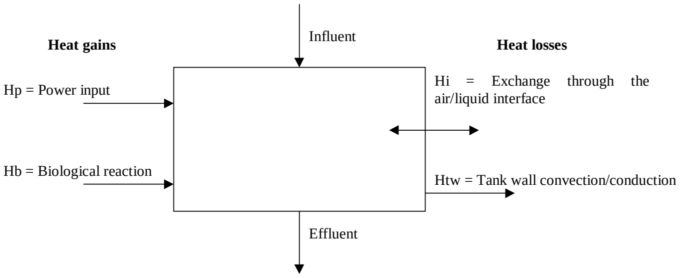

Fig. 1. Overview of the heat exchanges over the basin according to the simple model.

Table 1
Heat losses/gains—Simple model

| Term | Equation | Parameter | | | |
|---|---|---|---|---|---|
| | | Symbol | Description | Value | Unit |
| Hi | Ui $A(T_a-T_w)$ | Ui | Heat coefficient | Calculated | W/m$^2$ K |
| | | $A$ | Basin area | Variable | m$^2$ |
| | Subsurface aeration: | $T_a$ | Air temperature | Variable | K |
| | Ui = 25 | $T_w$ | Water temperature | Variable | K |
| | Surface aeration: | $V$ | Volume of the tank | Variable | m$^3$ |
| | Ui = 11.4$NP_{aer}/V$ | $P_{aer}$ | Aerator power | Variable | W |
| | | $N$ | Number of aerators | | |
| Htw | Htw = $U_w\mathrm{Ag}(T_w-T_e)$ | $U_w$ | Overall heat transfer coefficient for basin wall/bottom | Variable | W/m$^2$ K |
| | | $T_e$ | Soil temperature | Variable | K |
| | | Ag | Wall + bottom area | Variable | m$^2$ |
| Hp | Hp = $P_{aer}N$ | $P_{aer}$ | Aerator power | Variable | W |
| | | $N$ | Number of aerators | | |
| Hb | Hb = 4.1 OC (Cs − $C$)/Cs | OC | Oxygenation capacity | Variable | kgO$_2$/h |
| | | Cs | Concentration of oxygen at saturation | Calculated | mg/L |
| | | C | Concentration of oxygen in the tank | Variable | mg/L |

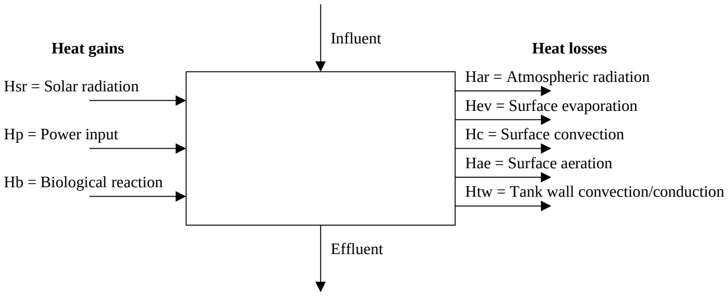

Fig. 2. Overview of the heat exchanges over the basin according to the complete model.

Table 2
Heat losses/gains—Complete model

| Term | Equation | Parameter | | | |
|---|---|---|---|---|---|
| | | Symbol | Description | Value | Unit |
| Har | $\varepsilon\sigma(T_w+273)^4A-(1-\lambda)\beta\sigma(T_a+273)^4A$ | $\varepsilon$ | Water emissivity | 0.97 | Dimensionless |
| | | $\sigma$ | Stefan Boltzman constant | $5.67e^{-8}$ | $W/m^2/K^4$ |
| | | $T_w$ | Water temperature | Variable | K |
| | | $A$ | Tank area | Variable | $m^2$ |
| | | $\lambda$ | Water reflectivity | 0.03 | Dimensionless |
| | | $\beta$ | Atmospheric radiation factor | Variable | Dimensionless |
| | | $T_a$ | Air temperature | Variable | °C |
| Hev | $\mathrm{Hev}=4.18/3600/24 \times (1.145\times10^6(1-r_h/100) + 6.86\times10^4(T_w-T_a))e^{0.0604T_a}WA^{0.95}$ | $r_h$ | Relative humidity | Variable | % |
| | | $W$ | Wind speed | Variable | m/s |
| Hc | $Hc=\rho_a c_{pa} h_v A(T_w-T_a)$ | $h_v$ | Vapour phase transfer coefficient | Calculated | m/s |
| | $h_v=392A^{-0.05}W/3600\times24$ | $\rho_a$ | Density of air | Calculated | $kg/m^3$ |
| | $\rho_a=1.293(273/(273+T_a))$ | $c_{pa}$ | Specific heat of air | 1050 | J/kg/K |
| Hae | $\mathrm{Ha}=\mathrm{Has}+\mathrm{Hal}$ | Has | Sensible heat loss | Calculated | W |
| | Surface aeration: | Hal | Evaporative heat loss | Calculated | W |
| | $\mathrm{Has}=h_v\rho_a c_{pa}(T_w-T_a)A$ | $H_v$ | Vapour phase transfer coefficient | Calculated | m/s |
| | $h_v=392F^{-0.05}W/3600\times24$ | $W$ | Wind speed | Variable | m/s |
| | Subsurface aeration: | $F$ | Spray area of the aerators | Variable | $m^2$ |
| | $\mathrm{Has}=Q_a\rho_a c_{pa}(T_w-T_a)A$ | $Q_a$ | Air flow rate | Calculated | $m^3/s$ |
| | Surface aeration: | $Mw$ | Molecular weight of water | 18 | g/mol |
| | $\mathrm{Hal}=M_wQ_aLs/100/R((v_w(r_h+h_f(100-r_h)/(T_w+273))-v_ar_h/(T_a+273))$ | $Ls$ | Latent heat of evaporation | 2270 | J/g |
| | | $R$ | Universal gas constant | 62.631 | mmHg L/gmol $K^4$ |
| | $Qa=NFW$ | $v_w$ | Vapour pressure at water temp. | Variable | mmHg |
| | | $V_a$ | Vapour pressure at air temp. | Variable | mmHg |
| | | $h_f$ | Exit air humidity factor | Variable | Dimensionless |
| | | $N$ | Number of aerators | Variable | Dimensionless |

| | | | | | |
|---|---|---|---|---|---|
| Htw | $Htw = U_w Ag(T_w - T_e)$ | $U_w$ | Overall heat transfer coefficient for basin wall/bottom | Variable | W/m$^2$ K |
| | | $T_e$ | Soil temperature | Variable | K |
| | | $Ag$ | Wall + bottom area | Variable | m$^2$ |
| Hsr | $\text{Hsr} = \text{Hsr},0(1 - 0.0071 C_c^2)A$ | Hsr,0 | Solar radiation for clear sky conditions | Variable | W/m$^2$ |
| | $\text{Hsr},0 = (a - b\sin(2\pi d/366 + c))4.18$ | | | | |
| | $a = 95.1892 - 0.3591k - 8.4537 \times 10^{-3}k^2$ | $K$ | Latitude of the site | Variable | Degree |
| | $b = -6.2484 + 1.6645k - 1.1648 \times 10^{-2}k^2$ | $C_c$ | Cloud cover | Variable | Tenths |
| | $c = 1.4451 + 1.434 \times 10^{-2}k - 1.745 \times 10^{-4}k^2$ | $d$ | Day of the year (1–365) | Variable | Dimensionless |
| Hp | $\text{Hp} = NP_{\text{aer}}$ | $P_{\text{aer}}$ | Aerator power | Variable | W |
| Hb | $\text{Hb} = h\Delta S$ | $h$ | Heat produced from degradation of organics | 7531 | J/gCOD |
| | | $\Delta S$ | Substrate removal rate | Variable | gCOD/s |

relationships)

$$\Delta H = \text{Hsr} + \text{Hp} + \text{Hb} - \text{Har} - \text{Hev} - \text{Hc} - \text{Hae} - \text{Htw}. \quad (3)$$

A complete description of the model can be found in Talati and Stenstrom [5] and Sedory and Stenstrom [8].

As seen in Table 2, the complete model requires an important number of input data, with different levels of uncertainty. To reduce this number, Namèche and Vasel [4] proposed to measure the solar radiation and the evaporation, rather than predict them with the model.

The heat balance over the basin consists in finding the water temperature for which the net heat exchange equals the enthalpy exchange (Eq. (1)). The solver of Excel has been used for this purpose.

### 2.2. Application to an aerated lagoon

The models have been applied to an aerated lagoon (10,000 m$^3$) located in the North of France, treating industrial wastewater (10–40 tonnes of COD per day). During winter time, the lagoon's COD removal efficiency is lower due to low temperature. Data were either measured at the plant or provided by a local weather station. A 10-day measuring campaign performed in April 2000 was first used to validate the models. Estimated temperatures throughout the year 2000 for each and every month were further calculated to compare the models between them.

The data required to estimate the equilibrium temperature using the model of van der Graaf [11] or the model of Talati and Stenstrom [5] are summarized in Tables 3 and 4 for the estimation concerning the 10-day measuring campaign. Table 5 presents the data used to estimate the monthly average temperature.

## 3. Results and discussion

### 3.1. Heat exchange terms

The heat exchanges considered in both models are depicted in Figs. 3 and 4.

In both models the heat losses through the walls can be neglected. While the simplified model aggregates all the terms involving a heat transfer through the gas/liquid interface (Hi = Hsr + Hae + Hc + Hev + Har), the complete one details these terms.

### 3.2. Temperature prediction

The temperatures predicted by both models have been compared to the measured temperature during the 10-day measuring campaign, and are presented in Table 6.

Table 3
Data required in the simple model

| Parameter | Value | Unit | Source |
|---|---|---|---|
| Tank area, $A$ | 4500 | $m^2$ | Design data |
| Tank volume, $V$ | 10,000 | $m^3$ | Design data |
| Wastewater flow rate, $Q_w$ | 0.00525 | $m^3/s$ | On site measurement |
| Influent temperature, $T_i$ | 23.3 | °C | On site measurement |
| Power input, $P$ | 55,000 | W | Design data |
| Heat transfer coeff. wall, Uw | 1 | W/$m^2$/°C | Estimated |
| Air temperature, $T_a$ | 8.2 | °C | On site measurement |
| Soil temperature, $T_e$ | 8 | °C | Estimated |
| Oxygenation capacity, OC | 16 | kg $O_2$/h | Design data |
| Oxygen concentration at saturation, Cs | 11.3 | mg/L | Estimated |
| Oxygen concentration, $C$ | 2 | mg/L | On site measurement |
| Wall + bottom area Ag | 4500 | $m^2$ | Design data |

Table 4
Data required in the complete model

| Site specific data | | | Meteorological data[2] | | | Process parameter[3] | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Value | Unit | Parameter | Value | Unit | Parameter | Value | Unit |
| Latitude, $k$[a] | 50 | ° | Vapour pressure at, $T_w v_w$[b] | 8.9 | mmHg | Wastewater flow rate, $Q_w$[c] | 0.00525 | $m^3/s$ |
| Tank area, $A$[a] | 4500 | $m^2$ | Vapour pressure at, $T_a v_a$[b] | 6.4 | mmHg | Influent temperature, $T_w$[c] | 23.3 | °C |
| Number of aerators, $N$[a] | 5 | — | Air temperature, $T_a$[d] | 8.2 | °C | Substrate removal rate, $\Delta S$[c] | 0.021 | kgCOD/s |
| Aerator spray area, $F$[a] | 6 | $m^2$ | Wind speed, $W$[d] | 5.0 | m/s | Day of the year d | 106 | |
| Power input, $P$[a] | 55 | kW | Relative humidity, $r_h$[d] | 79 | — | | | |
| Air Humidity factor, $h_f$[b] | 0.9 | | Cloud cover, $C_c$[d] | 5 | Tenths | | | |
| Heat transfer coeff. wall, Uw[b] | 1 | W/$m^2$/°C | Atmospheric radiation factor, $\beta$[b] | 0.8 | | | | |
| | | | Soil temperature, $T_e$[b] | 8 | °C | | | |

[a] Design data.
[b] Estimated.
[c] Daily measurements.
[d] From a meteorological station located in Lille, 30 km from the wastewater treatment plant.

Table 5
Data used to perform monthly estimation throughout the year 2000

| Month | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ta (°C)[1] | 3.0 | 3.0 | 6.0 | 8.0 | 12.0 | 15.0 | 17.0 | 17.0 | 15.0 | 11.0 | 6.0 | 4.0 |
| $W$ (m/s)[1] | 6.1 | 6.7 | 6.7 | 5.0 | 4.4 | 4.4 | 4.4 | 3.9 | 4.4 | 4.4 | 5.0 | 5.6 |
| $r_h$[a] | 88 | 85 | 82 | 79 | 78 | 79 | 78 | 78 | 83 | 87 | 89 | 90 |
| Qw ($m^3$/s)[b] | 0.26 | 0.26 | 0.27 | 0.27 | 0.29 | 0.29 | 0.31 | 0.31 | 0.33 | 0.29 | 0.26 | 0.23 |
| $T_{in}$ (°C)[2] | 25.8 | 25.1 | 27.8 | 28.5 | 27.5 | 28.0 | 31.0 | 31.3 | 29.0 | 29.5 | 27.5 | 21.7 |
| $\Delta S$ (tCOD/d)[b] | 27.7 | 18.6 | 19.5 | 20.1 | 21.1 | 21.1 | 31.8 | 30.4 | 38.1 | 36.4 | 27.9 | 12.7 |

[a] From the meteorological station.
[b] Monthly averages from daily measurements at the plant.

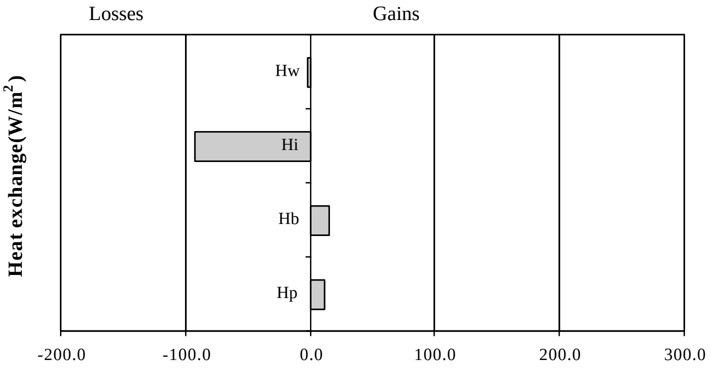

Fig. 3. Heat exchanges according to the simple model.

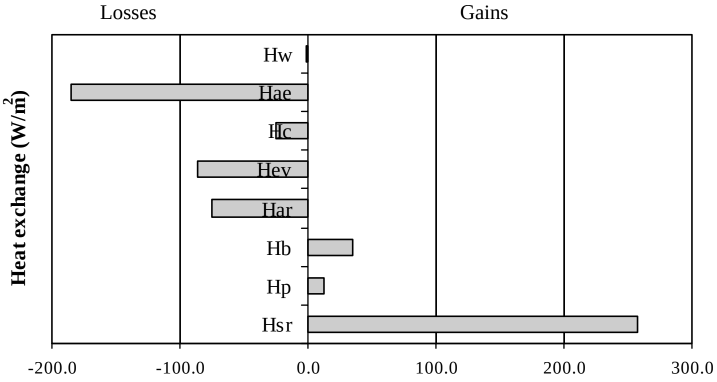

Fig. 4. Heat exchanges according to the complete model.

Table 6
Equilibrium temperatures estimated by the models

| $T_{measured}$ (°C) | Simple model | | | Complete model | | |
|---|---|---|---|---|---|---|
| | $T_{estimated}$ (°C) | Diff (°C) | Relat. Diff (%) | $T_{estimated}$ (°C) | Diff (°C) | Relat. Diff. (%) |
| 10.1 | 9.7 | −0.4 | −4.1 | 10.0 | −0.1 | −0.7 |

Both models give a good estimation of the equilibrium temperature.

### 3.3. Monthly averages prediction

The models have been used to predict the monthly average temperatures in the lagoon obtained on the basis of meteorological and operational data for the year 2000. The estimated temperatures are presented in Fig. 5. The temperatures predicted by both models are close. They may therefore both be used to estimate the temperature variation through the year.

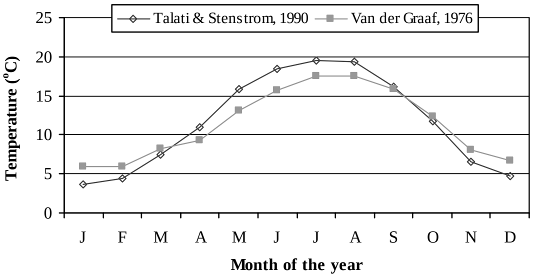

Fig. 5. Prediction of monthly average temperature ($T_w$).

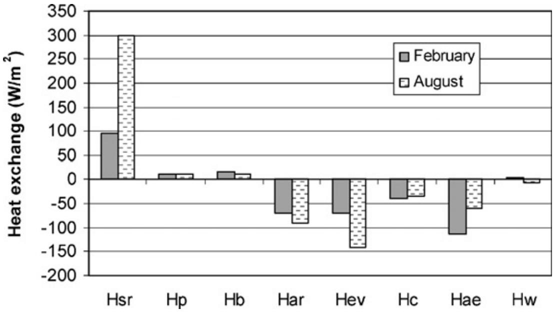

Fig. 6. Comparison of heat exchange breakdowns in winter and summer.

### 3.4. Breakdown of the heat exchanges

Using the complete model, the heat exchange terms per $m^2$ of tank area have been calculated for February and August. The obtained breakdowns are depicted in Fig. 6.

The results obtained show that the solar radiation is the main energy source for the lagoon (75% and 95% of the heat gain in winter and summer, respectively). Energy is mainly lost through aeration, and evaporation and radiation (20–40% of the heat loss for each). These results are similar to the literature data [5,4]. Fig. 6 also points out that if the energy gains/losses are rather well-balanced during warm weather, the losses are more important during winter, which may induce a significant decrease in temperature and the consequent COD removal deficiencies encountered.

The fact that the estimated temperature with the complete model is higher in summer and lower in winter than the one calculated with the simple model (see Fig. 5) may be attributed to the difference observed in the solar radiation, much higher in summer time. This difference is not directly taken into account in the simple model.

## 4. Conclusions

This note described two models to estimate the equilibrium temperature in aerated basins. They differ by their degree of complexity and therefore by the input data they require. The equations used to calculate the different heat exchange terms are presented, and the models are applied to data of an aerated lagoon. Both models have been validated using a 10-day measuring campaign: they give a temperature close to the measured one. They also give similar monthly estimated temperature, on the basis of meteorological data and process performances. Therefore they may both be used in this case to estimate the equilibrium temperature, the more complex model giving, in addition, a complete breakdown of the heat exchanges.

The models should however be further validated on data obtained for basins under different conditions (e.g. other types of aeration systems, such as horizontal rotors, diffused aeration, sites with different meteorological conditions, nitrifying plants, etc.).

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