Modeling and experimental validation of water temperature in a fish rearing tank

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ABSTRACT
This study describes the modeling of a fish rearing tank. Numerical computations have been performed for a typical day in the month of January, 2005 for the composite climate of New Delhi. This model has been developed by considering the effect of heat losses e.g. conduction, convection, radiation and evaporation. The governing equations are numerically solved with Matlab-7.0 software to predict the water temperature. The model has been validated with the experimental data. It is inferred that the predicted and experimental values of water temperature exhibited fair agreement with coefficient of correlation (r = 0.90) and root mean square percent deviation is (e = 1.67%).

Introduction
In any pond, solar radiation provides the heat inputs while the heats of evaporation, convection and radiation were responsible for the heat loss (Klemetson and Rogers 1985). Heat losses from the pond surface are most heavily influenced by wind velocity and the temperature difference between the pond and surrounding air. A pond exposed to the atmosphere, exchanges heat by the way of four mechanisms: a) evaporation b) convection c) radiation and d) conduction. Each of these is influenced by different parameters. Among the four mechanisms, evaporation is the largest component of the total heat loss from the pond. Heat loss by evaporation from the pond surface involves a state change of water from liquid to water vapor. The energy required for this transformation through the latent heat of vaporization is taken from the energy stored within the water column. Convection is the transfer of heat from one part of a fluid to another part, at a lower temperature by mixing of fluid particles. It is dependent upon the wind velocity, the mixing of the water within the pond, and temperature gradient between the pond, and ambient air (Klemetson and Rogers, 1985). Radiative heat loss which depends primarily on the temperature difference between the pond surface and the surrounding air temperature. The final mode of heat loss is the conduction. The phenomenon of heat conduction is a process of propagation of energy between the particles of a body which are direct contact and have different temperatures.
This is the loss associated at the soil-water interface and sub soil layers. Conduction is by far the smallest and in many calculations is simply omitted.

Open pond temperature has been modeled by several researchers (Klemetson and Rogers, 1985; Cathcart and Wheaton, 1987 and Noel et al., 1996), based on surface water temperature. The MATP model by Klemetson and Rogers (1985) was developed for aquacultural pond temperatures throughout the year, assuming completely air tight condition (no wind and 100% relative humidity) over the pond surface. Cathcart and Wheaton (1987) developed a model for predicting the temperature of turbid freshwater ponds by using pond surface temperature. Noel et al. (1996) determined the water temperature of a parallel piped pond of variable geometry.

Presently, there is a large body of literature available to predict the temperature distribution in aquatic systems, but mostly are based on salt-stratified solar ponds. The prediction of water temperature is of importance to aquaculturist since temperature directly affects the growth of fish and also influences resistance to disease. A reliable temperature prediction model would be useful to the aquaculturist to monitor the pond environment and for decision on support systems.

Keeping in view the importance of aquaculture sector, a study has been carried out in this communication, to develop a model for predicting hourly water temperature considering heat losses and gains in a fish rearing tank.

**Materials and methods**

The experiment was conducted at Indian Institute of Technology (IITD), New Delhi (Latitude-28°35' N, Longitude – 77°12' E and an altitude of 216 m above mean sea level). A cylindrical tank of capacity 636 l was used for the experiment. The experimental tank was fabricated from PVC liner supported by aluminum sheet of 0.9 m diameter and 1.2 m height and same was placed on 0.1m thick brick platform. The schematic view of the experimental set-up and the energy flow diagram are shown in Fig.1a and b. The hourly water temperature (T_w) and ambient air temperature (T_a) were measured by calibrated alcohol- filled, glass-bulb thermometer having least count of 1°C. The thermometer to measure ambient temperature (T_a) was shaded from direct sun light. A digital humidity meter (Model- Lutron HT-3003) was used to measure the relative humidity (γ) with a least count of 0.1%. The air velocity was measured with an electronic digital anemometer (Model - Lutron AM4201). It had a least count of 0.1 m/s with ± 2% on full-scale range of
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0.2-40.0 m/s. Total solar intensity data was recorded on a horizontal surface at hourly basis. Solar intensity was measured by a Solarimeter, locally named Suryamapi (Make: CEL, India). It had a least count of 2 mW/cm² with ±2% accuracy over the full-scale range of 0-120 mW/cm². The hourly observations were taken for duration of 24 hours with regular and equal time intervals of 60 minutes once in a week during November, 2004 to February, 2005.

However, the experimental validation was done for a typical day on 5.1.2005. Since, January was the coldest month for Delhi during the experimental period.

Thermal Analysis

Energy balance equations

In order to write energy balance equations, the following assumptions have been made-

(i) Heat flow is one dimensional in a quasi-steady state condition

(ii) No water exchange during the experimentation

(iii) Fish in the tank are very less in number and small in size

(iv) Heat storage capacity of the material of the tank is neglected

Energy balance equation in open pond

\[ \sum \alpha \cdot \frac{dT}{dt} + U(T_a - T) + U(T_e - T) + a(T_e - T) = B(t) \]

(1)

At larger depths, the temperature of ground is assumed to be equal to ambient air temperature, \( T_\infty = T_a \) (Khatry et al., 1978 and Ghosal et al., 2005), then Eq. (1) can be written in the form of first order differential equation as

\[ \frac{dT}{dt} + aT_e = B(t) \]

(2)

where

\[ B(t) = \frac{\alpha \cdot U \cdot (T_a - T)}{(MC)_t} \]

\[ a = \frac{(UA)_{eff}}{(MC)_t} \]

\[ (UA)_{eff} = A_a U_a + A_s U_s + A_b U_b \]

\[ h_w = 2.8 + 3.0 \nu \] (for 0 ≤ \( \nu \) ≤ 7 m/s by Watmuff et al., 1977)

\[ T_{sky} = 2T_a - T_w \] (Noel et al., 1996)

\[ P(T_e) = \exp\left(\frac{25.317 - 5144}{273 + T_e}\right) \] (Fernandez and Chargoy, 1990)

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Tiwari, 2002)

\[ h_w = \frac{16.273 \times 10^7 \cdot h_w \cdot (P_e - y P)}{T_e - T_a} \] (Cooper, 1973)
Analytical solution of Eq. (2) can be written as

\[ T_w = \frac{B(t)}{a} (1 - e^{-at}) + T_w e^{-at} \]  

(3)

where \( T_w \) is the water temperature at \( t = 0 \) and \( \overline{B(t)} \) is the average of \( B(t) \) for the time interval 0 to \( t \) and \( a \) is a constant during the time. From Eq. (3) the water temperature can be determined for analysis.

**Statistical Analysis**

**Coefficient of correlation (r)**

When predicted values are validated with the experimental data then correlation between predicted and experimental values is presented with a coefficient known as coefficient of correlation. The coefficient of correlation can be evaluated with the following expression (Chapra and Canale, 1989).

\[
r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}}
\]  

(4)

**Root mean square of per cent deviation (e)**

The predicted values are validated with experimental data. The closeness of predicted values and experimental data can be presented in terms of root mean square of per cent deviation. The expression used for this purpose is as follows (Chapra and Canale, 1989).

\[
e = \sqrt{\frac{\sum_{i=1}^{n}(e_i)^2}{n}}
\]  

(5)

where \( e_i = \frac{X_{\text{pred}} - X_{\text{exp}}}{X_{\text{pred}}} \)

**Numerical results and discussion**

The model has been solved with the help of the computer programme in MATLAB. Numerical calculations were made corresponding to the hourly variations of solar intensity, ambient air and water temperature, wind velocity and relative humidity (averaged over one hour period) for a typical winter day (05.01.2005). The input design parameters used for experimental validation is given in Table 1. The output of the programme gives the predicted hourly average water temperature (Eq.3). The hourly variations of total solar intensity, ambient air \( (T_a) \) and water temperature \( (T_w) \) have been presented in Fig.2. The values of \( I(t), T_a \) and \( T_w \) have been used as the input parameters in the model. From the figure it was observed that the ambient air

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>A_a, A_b</td>
<td>0.636 m³</td>
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<tr>
<td>A_s</td>
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<tr>
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<tr>
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<td>ν</td>
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<tr>
<td>γ</td>
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increases with increase of solar intensity and vice-versa. The water temperature increases slowly due to smaller exposed surface area and larger depth, and at large variations of air temperature. Hourly variations of water temperature and mass evaporated are plotted in Fig. 4. From this figure, it is seen that mass transfer depends on water temperature and other climatic parameters. Mass transfer increases with increase of water temperature. Larger mass transfer was observed at higher temperature and declined with lowering of temperature.

Whereas incase of water temperature, it increases slowly due to higher specific heat capacity of water and decrease at night time due to drop of air temperature. The hourly variations of predicted and experimental water temperature are presented in Fig. 5. From the figure, it is noted that the water temperature reaches maximum between (14:00 to 18:00) during sunshine hours while minimum values were observed at night time between (1:00 to 5:00) due to
fluctuation of air temperature and fast release of heat at night time. The predicted water temperature exhibited good agreement with the values of coefficient of correlation \((r = 0.90)\) and root mean square percent deviation \((e = 1.67\%)\), respectively. The model presented in this paper is quite simple to predict water temperature. It can be applicable to use for any aquaculture pond.

**Nomenclature**

- \(A\) area \((m^2)\)
- \(A_t\) top surface area of the tank \((m^2)\)
- \(A_b\) bottom surface area of the tank \((m^2)\)
- \(A_s\) side surface area of the tank \((m^2)\)
- \(C\) specific heat \((J/kg \cdot ^\circ C)\)
- \(e\) root mean square of percent deviation \((\%)\)
- \(h_i\) heat transfer coefficient from tank wall to ambient air \((W/m^2 \cdot ^\circ C)\)
- \(h_{cw}\) convective heat transfer coefficient from water to ambient air \((W/m^2 \cdot ^\circ C)\)
- \(h_{rw}\) radiative heat transfer coefficient from water to sky \((W/m^2 \cdot ^\circ C)\)
- \(h_{ew}\) evaporative heat transfer coefficient from water to ambient air \((W/m^2 \cdot ^\circ C)\)
- \(I(t)\) solar radiation falling on water surface \((W/m^2)\)
- \(K_g\) thermal conductivity of ground \((W/m \cdot ^\circ C)\)
- \(K_p\) thermal conductivity of PVC liner \((W/m \cdot ^\circ C)\)
- \(K_{al}\) thermal conductivity of aluminum sheet \((W/m \cdot ^\circ C)\)
- \(K_b\) thermal conductivity of brick \((W/m \cdot ^\circ C)\)
- \(L_g\) thickness of ground \((m)\)
- \(L_p\) thickness of PVC liner \((m)\)
- \(L_b\) thickness of brick \((m)\)
- \(L_{al}\) thickness of aluminum sheet \((m)\)
- \(M\) mass \((kg)\)
- \(P_w\) saturated vapor pressure at water temperature \((Pa)\)
- \(P_a\) saturated vapor pressure at air temperature \((Pa)\)
- \(r\) Correlation coefficient \((\text{decimal})\)
- \(T_w\) water temperature \((^\circ C)\)
- \(t\) time in seconds
- \(T\) temperature \((^\circ C)\)
- \(U_b\) overall heat transfer coefficient through bottom \((W/m^2 \cdot ^\circ C)\)
- \(U_t\) total top loss coefficient \((W/m^2)\)
- \(U_s\) overall heat transfer coefficient through side of the tank \((W/m^2 \cdot ^\circ C)\)
- \(v\) velocity of air \((m/s)\)
- \(X\) experimental water temperature
- \(Y\) predicted water temperature

**Greek Letters**

- \(\alpha\) absorptivity \((\text{decimal})\)
- \(\gamma\) relative humidity \((\text{decimal})\)
- \(\varepsilon\) emissivity, dimensionless
- \(\rho\) density \((kg/m^3)\)
- \(\sigma\) stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{W/m}^2 \text{k}^4)\)
- \(\infty\) infinity \((\text{ground at larger depth})\)

**Subscripts**

- \(a\) ambient air
- \(g\) ground
- \(w\) water
References


