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Numerical prediction of heat transfer characteristics based on monthly temperature gradient in algal open raceway ponds

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ABSTRACT

This paper presents a novel empirical correlation to estimate the heat transfer in raceway ponds for different pond sizes and depths. The correlation involves the calculation of Nusselt number. Heat transfer in outdoor raceway ponds was modeled with the effects of pond design, hydrodynamics, and environmental conditions. Monthly average water temperature, Nusselt number, and Prandtl number were used to examine the heat transfer phenomena between pond and its surroundings. A novel relation was also employed to estimate the amount of monthly evaporated water from the raceway ponds. Different aspect ratios, pond depths, and paddle wheel rotational speeds were considered to evaluate the effect of pond geometry and turbulent mixing on heat transfer. The use of empirical relation is an effective approach in designing raceway ponds to estimate heat loss in ponds. Algal productivity decreased with increasing amount of evaporated water. Moreover, the environmental conditions, pond design, and turbulent mixing significantly affected the heat transfer rate and the optimum water temperature for algal growth.

1. Introduction

Outdoor raceway ponds are widely used for mass cultivation of microalgae because of their cost and design effectiveness. Heat transfer or the exchange of thermal energy between the raceway pond and atmosphere significantly affects algae growth. Pond temperature depends on the geometrical design of raceway pond, solar intensity, ambient air temperature, wind speed, and evaporation [1,2]. Solar irradiance and temperature are important environmental variables that contribute to heat transfer between pond and its surrounding. Maximum utilization of solar energy is achieved when the water temperature is optimal. Solar irradiance may become harmful when the water temperature falls below the optimum value (28–35 °C) [3–6]. Rate of algal cell growth increases until the water temperature reaches the optimal value and decreases beyond the optimal value of the temperature [7]. Evaporation is another important component of heat transfer that plays a significant role in the exchange of thermal energy between raceway pond and atmosphere [8]. Evaporative cooling causes a significant water loss from the pond and affects the optimal water temperature. Raceway ponds use CO_2 less efficiently because of significant water losses to atmosphere [8,9]. Laws et al. [10] developed an algal cultural system incorporated with airfoils to increase the utilization of the flashing light effect by generating systematic turbulent mixing. Solar energy conversion efficiency increases twice in an experimental setup with airplane wing-shaped airfoils. The productivity of raceway ponds is also affected by the seasonal and variations of climatic light and temperature [11]. Bosca et al. [12] reported that photosynthetic rate increases significantly when algal cells are mixed particularly in sunrise and sunset hours with optimal temperature conditions [12]. However, experimental estimation of the heat transfer between pond and atmosphere is difficult and expensive because of the complex variations in different parameters, including geometrical design of raceway pond, solar intensity, ambient air temperature, wind speed, and evaporation [1].

Modeling heat transfer phenomena in algal ponds by using computational fluid dynamics (CFD) is a cost-effective technique to maximize algal productivity under actual atmospheric conditions. Numerous numerical techniques have been proposed to model algal productivity under time-dependent conditions of solar irradiance and temperature [13–15]. James and Boriah [16] presented a CFD model to incorporate the effects of various factors associated with pond design, hydrodynamics, and atmospheric conditions. The diurnal fluctuations in the temperature are less prominent with increasing water depth. With the increase in pond depth, the water temperature remains close to the optimal value

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Nomenclature

AR	aspect ratio (1)
c	water vapor concentration (mol/m^3)
c_{vap}	concentration of water vapor (mol/m^3)
d	water or pond depth (m)
D	diffusion coefficient (m^2/s)
D_h	hydraulic diameter (m)
$e_b(T)$	blackbody hemispherical total emissive power (W/m^2)
F_{amb}	ambient view factor (1)
F_{ext}	external view factor (1)
G_{amb}	ambient irradiation (W/m^2)
H_{vap}	latent heat of vaporization (kJ/mol)
h	heat transfer coefficient of air (W/(m^2 K))
I_s	incident radiative intensity coming from the Sun (W/m^2)
j	diffusive flux in z-direction (mol/m^2 s)
J	radiative flux or radiosity (W/m^2)
k	water thermal conductivity (W/(m K))
L	pond length (m)
m_w	amount of evaporated water (kg)
M_w	molar mass of water (kg/mol)
Nu	Nusselt number (1), hD_h/k
n	transparent medium refractive index (1)
p_{sat}	saturation pressure (Pa)
Pr	Prandtl number (1), ν/α

q	heat flux (W/m^2)
R_g	ideal gas constant (J/mol K)
Re	Reynolds number based on hydraulic diameter (1)
Sc_T	Schmidt number (1)
t	time in hours (h)
T	water temperature (K)
T_a	monthly mean ambient temperature (K)
T_{amb}	ambient temperature (K)
T_s	soil temperature (K)
u	water velocity vector (m/s)
u_a	mean air speed (m/s)
W	channel width (m)
$\otimes$	outer vector product operator

Greek symbols

α	thermal diffusivity (m^2/s)
ρ	water density (kg/m^3)
μ	water viscosity (Pa s)
ω	revolutions per minute (1/s)
ε	surface emissivity (1)
σ	Stefan–Boltzmann constant ($W/m^2\ K^4$)
ν	turbulent kinematic viscosity (m^2/s)
φ	relative humidity (%)

and in turn the algal growth is enhanced. However, paddle wheel was not considered in their results, and a constant flow rate was used to circulate water in pond [16]. Lack of temperature control significantly limits microalgal culture in outdoor ponds. To solve this problem, Waller et al. [17] developed a new raceway pond design; their design controls and regulates temperature by adjusting the water surface area. Drewry et al. [2] and Gharagozloo et al. [1] developed a CFD code to model the heat transfer between pond and atmosphere based on species, pond design, water quality, and environmental conditions. However, both studies used a 2D geometry (0.2 m deep × 1 m long) of the cross-section of raceway pond in their simulations, which do not effectively explain the heat transfer phenomena in the entire raceway pond [1,2]. Empirical relation is another approach to present experimental or numerical results based on the aforementioned complex variables so that they can be utilized with most generality and effectiveness [18]. Numerous correlations have been developed experimentally and numerically to predict the heat transfer in various industrial and chemical applications [19–25]. However, a correlation to estimate the heat transfer in raceway ponds is not available and therefore must be numerically developed to generalize the obtained results [23,24,26]. Previous studies also lacked results with regard to the effects of turbulent mixing (paddle wheel rotational speeds) and pond geometry on heat transfer. Therefore, a numerical study with 3D algal pond must be conducted to characterize completely and optimize the heat transfer phenomena with the effects of pond geometry, hydrodynamics, and environmental conditions. The numerical result data should also be generalized by presenting them in an empirical correlation form [23,24,26].

This study aimed to investigate the heat transfer phenomenon that occurs between raceway pond water and its surroundings with the effects of pond geometry, solar intensity, ambient air temperature, wind speed, relative humidity, soil temperature, and evaporation [1,2]. The fluid dynamic characteristics of air and pond water with the effect of paddle wheel were initially computed. These velocity fields were then used to solve the equations for heat transfer and evaporation (transport of diluted species) simultaneously. The monthly water temperature, Nusselt number (Nu), and Prandtl number (Pr) were evaluated to investigate the heat transfer phenomena between pond water and atmosphere. Various pond sizes (aspect ratio), pond depths, and paddle wheel rotational speeds were considered to analyze the effects of turbulent mixing on the preceding heat transfer parameters. A novel relation was presented to examine the effect of evaporation by estimating the amount of monthly evaporated water from the pond surface [9]. A novel and general empirical relation was also proposed to calculate the heat transfer in raceway ponds of different sizes and depths [23,24,26].

2. Mathematical modeling

Fig. 1(a) presents the basic geometry of the experimental raceway pond of Weissman et al. [9], with a length (L) of 23 m and a channel width (W) of 2.25 m. A 2D paddle wheel (diameter = 0.6 m) with six blades (0.55 m × 0.04 m) was used in this study to generate turbulent flow in the raceway pond. The boundary-connected coupling methodology was conducted to import the pulsating effects of the 2D paddle wheel in the 3D raceway pond [27,28]. A dimensionless quantity, that is, aspect ratio (AR), was used to study the effects of pond geometry on heat transfer:

$$AR = \frac{\text{Channel width (m)}}{\text{Water or pond depth (m)}} = \frac{W}{d} \tag{1}$$

This study employed three different values of ARs (i.e., 5, 10, and 15) with different paddle wheel rotational speeds, water depths, monthly differences in solar irradiance, relative humidity, wind speed, and ambient and soil temperatures to investigate their effects on the heat transfer parameters. The effects of the presence and motion of algal cells (concentration and dispersion) on the heat transfer process are out of the scope of this study, so they were not considered.