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Pond Evaporation Systems for Harvesting Algae

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ABSTRACT

The production of algae is important because it is used as a source of energy and fertilizer. Algae production and quality depend on the evaporation of water. Therefore, in this paper are reviewed different types of evaporation systems to develop a suitable evaporation measurement technique for large scale algae production. The temperature at air-water interfaces; the humidity; the air-water surface area; the air temperature and the airflow rate above water surface are identified as influencing factor that control evaporation. Usually, evaporimeters, empirical equations, and analytical methods are used to determine the rate of evaporation. In the evaporimeter method, the amount of evaporation is determined from the deviation of water level and the meteorological data but the accuracy is questionable. In the empirical equations method, the equations are developed based on boundary conditions of experimental data where the accuracy is frequently uncertain. The analytical methods are often the least accurate because of their theoretical basis.

Keywords: Evaporation rate, Algae, Algae cultivation, harvesting Algae

1.0 Introduction

Since the industrial revolutions, fossil fuels, such as coal and petroleum have been the main fuel source in the world. The combustion of fossil fuels contributes to atmospheric climate change. Therefore alternative fuel sources are increasingly important. Algae can be used a resource by turning it into bio-fuel [1]. In algae cultivation and harvesting, major components of water management concern its usage, losses, and quality. Large amount of energy needed to manage the water is associated with algae cultivation systems. The total amount of water required is partially used for supporting a culture toward the target biomass productivity level and to replace water that is natural lost or evaporation lost. In part, this stems from cultivation of dilute biomass concentrations of conventional systems, such as raceway ponds as well as flat plate and tubular photo-bioreactors (PBRs), where algae cells are suspended in the liquid phase. These technologies require (a) in excess of 6000 gallons of water to cultivate 1 gallon of algae oil, (ii) a large amount of energy for pumping and circulating a dilute algae suspension as large as 385.71 MJ/kg of cultivated algae, and (iii) energy intensive dewatering and biomass concentration processes for downstream use of the biomass resulting in energy requirements of up to 82 MJ/ kg algae biomass produced [2]. Separating algae from algal biomass concentrating are known as harvesting. The algae harvesting involve recovering, dewatering and drying algae biomass. Selection of harvesting processes depends on the nature of algae. The most common harvesting methods are screening, coagulation, flocculation, sedimentation, flotation, filtration and centrifugation [3]. Evaporation is the opposite phenomenon of condensation. Condensation is a process that forms liquid from gaseous phase. In the evaporation process, liquid molecules are vaporized from a free surface of liquid and enter the gaseous phase. In this process, when a portion of molecules of the free liquid surface has received sufficient heat energy from surrounding sources, the molecules would escape from the liquid surface [4]. If the relative humidity is less than 100%, then the liquid vapor molecules is absorbed by the air. As a result, the liquid temperature will go down until the equilibrium is reached. The water budget, energy budget, mass transfer, empirical equation and evaporation pan measurement methods are used to determine evaporation rate. The energy budget includes net radiation, energy need to evaporate water, sensible heat transfer etc. that require precise measurements. The mass transfer method is based on Dalton's law; give reasonably good results in many cases of potential evaporation rates. The use of empirical formulas requires extra attention to (a) difficulties in the measurement of variables related to evaporation, (b) limitation of range for the stated accuracy in the model and (c) difficulties in comparing one empirical method with other empirical methods due to method specification model. Finally, the evaporation pan method is the easiest method to measure the evaporation from free water surface. The deviation of water level directly determine over time from a sample of open water pan of specified dimensions and sitting subject to pan coefficient. In conclusion, determining the most suitable evaporation rate measurement method will depend on the availability of data collected from experiment. It also will be depending by the influence of the accuracy of the estimated evaporation rate.

1.1 Evaporation

Evaporation is the process by which water changes from liquid to vapor state. There are two phenomena involved in the evaporation system. The first phenomenon is the change of the phase and the second phenomenon is the transfer of vapor. The change of the phase from liquid to vapor requires energy to provide the latent heat of

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vaporization. Solar energy is the main source of energy to recover latent heat of vaporization in the pan evaporation method [4]. The ability to transfer vapor by evaporation from a surface to the surrounding air is subject to relative humidity, wind speed, air temperature, and concentration of liquid, vapor pressure of air on water surface etc. Evaporation process is separated from three categories as evaporation from open water body; actual and Potential evapotranspiration [4].

1.2 Evaporation from an Open Water Body

Evaporation from an open water body is the process where water transfer directly from reservoir's free water surface to the atmosphere. Generally, it is not possible to drive the equation for measuring the evaporation rate, using meteorological data onto. The difficulty arose out of the fact that this type of evaporation is affected by meteorological factors of solar radiation, difference in vapor pressure between water or liquid surface and the overlying air, relative humidity, air temperature, wind speed and atmospheric pressure.

1.3 Actual Evapotranspiration

Actual evapotranspiration includes the evaporation and transpiration from a land surface and its vegetation. It depends on the availability of water. Moist areas like the tropical rain forests have higher evaporation rates than arid regions. The amount of water that evaporates from the land surface depends on the amount that is contained in the soil. Transpiration is the process of water movement towards a plant, its evaporation aerial parts, such as from the leaf and stems of the plants. Plants absorb soil water through their roots. This water can be originated from deep down in the soil. Plants pump water from the soil to deliver nutrients to theirs leave. Foliage is the plant life or the plant ground cover of a region, life forms, structure spatial extent or any other specific botanicals or organic characteristics. The actual evapo-transpiration for any soil land surface depends on soil moisture status. It will be greater for a saturated soil than the unsaturated soil. The actual evapotranspiration can be determined by analysis of concurrent records of rainfall and runoff from watershed [4].

1.4. 3 Potential Evapotranspiration

Potential evapotranspiration is defined as the evapo-transpiration that would result there is always adequate water supply available to fully vegetate the surface. The potential evapotranspiration is the simplified form of actual evapotranspiration. Estimates of potential evaporation are generally used to represent evaporative demand. Conceptually, potential evaporation represents the maximum possible evaporation rate and is the rate that would occur under given meteorological conditions from a continuously saturated surface. Notionally, the concept of potential evaporation is simple. The practical implementation of the concept is problematic and ambiguous due to the many ways that potential evaporation can be, and has been, formulated. It is the actual evapotranspiration from a soil matrix which is held the constant at field capacity for spraying the land regularly.

2. 0 Evaporation Measurement Technique

An evaporation rate is expressed as the mass or volume of liquid water evaporated per area in unit of time usually in a day. The amount of evaporation depends on temperature, humidity, solar radiation, vapor pressure and wind speed **[5].** Generally, evaporation is higher at higher temperatures and also for liquids with lower surface tension. Therefore, an evaporation rate function is combinations of meteorological variables and the liquid properties. The amount of evaporation from a liquid or water surface is estimated by evaporimeter or Evaporation pan data; empirical equation methods for estimating evaporation rate; analytical methods for estimating evaporation rate etc.

2. 1 Evaporimeter or Evaporation pan data

In evaporimeter or evaporation pan data measurement system, pans containing water is exposed to the atmosphere. The water lost through the evaporation is measured in a regular interval or sample time. The pond evaporation (E) is equal to loss of water in the pan by evaporation (E_{pan}) within a sample time duration and pan coefficient (K) [5, 6].

$$E = K \times E_{pan} \tag{1}$$

Pan evaporation is combined the effects of climate elements such as humidity, temperature, rainfall, drought dispersion, solar radiation and wind speed. Evaporation is greatest on hot windy, dry, sunny days and is greatly reduced when clouds block the sun and when air is cool, calm and humid. The evaporation pan is used to hold water during observation periods for the determination of the quantity of evaporation at a given location. It is normally installed on a wooden platform set on the ground in a grassy location and an opened area to away from trees and other wind obstruction, which may affect the natural air flow in the area. The measurement of evaporation rates for this method is conducted using many types of the pan which are Class A evaporation pan, ISI standard evaporation pan, Colorado sunken evaporation pan, USGS floating evaporation pan etc. In this method, the evaporation rate is measured by the product of parameter pan coefficient with pan evaporation from the time formerly this method eliminates objectionable boundary effects of radiation on the side walls, heat to exchange between the atmospheres and the pan itself, wind action. Pan coefficient is a constant. It is dependent on the size, shape and pan material. Table-1 shows of pan coefficients for some types of the pan.

2.2 Class A evaporation pan

Class A evaporation pan is a large standardized pan containing water that represented open water in an open atmosphere. This pan is used to estimate the evaporative capacity of the atmosphere traditionally practiced for irrigation scheduling purpose. The pan consists of a shallow vessel according to a standard specification. Fig.1 shows the dimensions of standard class A evaporation pan [4, 8-12].

Table-1: Value of the evaporation pan coefficient [7].

SI. No	Types of pan	Average Value	Range
1	Class-A evaporation pan	0.70	0.60 – 0.80
2	ISI evaporation pan	0.80	0.65 – 1.10
3	Colorado Sunken evaporation pan	0.78	0.75 – 0.86
4	USGS Floating evaporation pan	0.80	0.70 – 0.82

It is made of galvanized iron sheets and installed on a wooden bed. The pan is filled water to a depth around 19 cm up to 20 cm. The free height of free water surface is measured with hook gauge and stilling, electronic sensor, naphthalene sensor, differential manometer, float indicators with pointer ruler etc. The difference between water level heights at two consecutive observed times are indicating the pan evaporation rate.

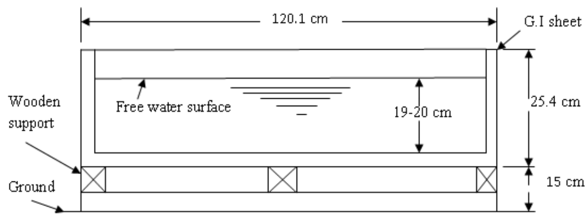

Fig. 1: Class A Evaporation Pan

2.1.3 ISI Standard Evaporation Pan

ISI standard evaporation pan is shown in Fig. 2 is a modified form of the class A evaporation pan. The pan consists of a shallow vessel made of copper sheets, tinned inside and painted outside. It is installed on a wooden grillage platform 10 cm above ground surface. The pan has small stilling well in which a fixed point gauge with Vernier scale is installed to measure the change in water level due to evaporation. The daily evaporation rate is computed from the difference between the observed water levels in the pan.

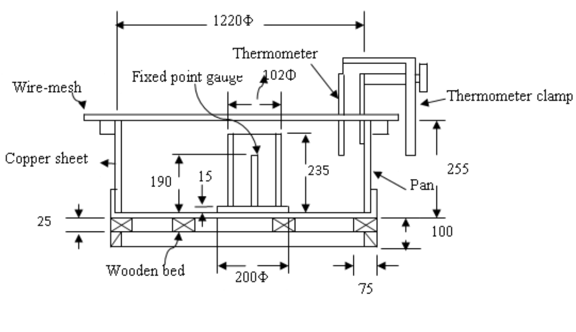

Fig. 2: ISI Evaporation Pan

2.1.4 Colorado Sunken Evaporation Pan

A Colorado sunken evaporation pan is shown in Fig 3. It is hidden into the ground such that the top level of the evaporation pan is at ground level. The pan is 92 cm squares in the plan and 46 cm in depth. It is made of unpainted galvanized iron sheets. The main disadvantage of this evaporation pan over the class A pan is the radiation and aerodynamic characteristics are closer to those of reservoir.

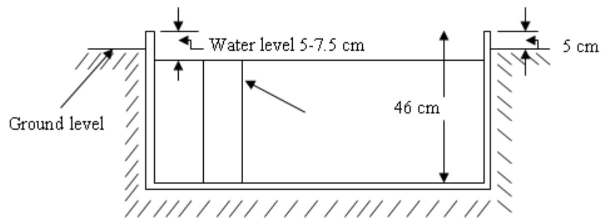

Fig. 3: Colorado Sunken Evaporation Pan

2.1.5 US Geological Survey Floating Evaporation Pan

A USGS floating evaporation pans is made according to the standard dimension of 90 cm squares in the plan and 45 cm in depth. It is supported by drum floats in the middle of a raft of size $4.25m \times 4.87m$. USGS floating evaporation pan is shown in Fig. 4. It is floating in a lake with a view to simulating the characteristic of a large body of water. The water level in the evaporation pan is kept at the same level as that of the lake. The diagonal baffles are built in the pan to reduce the wave action and wash. This type of evaporation pans is used only for geological surveys. The installation and maintenance cost are very high for this type of pan.

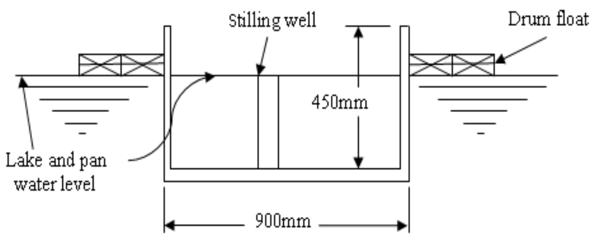

Fig. 4: Schematic diagram of USGS floating pan

2.1.6 Measurement of Water Level

The estimation of the evaporation is highly influenced by the accuracy in measuring the reduction of the water level. The water level reduction in the evaporation pan can be determined by using fixed point gauge and stilling or automatic method (Electronic sensor) or ruler scale with float pointer. The fixed point gauge consists of a pointer rod placed vertically at the center of a cylindrical well. The measuring tube has a cross sectional areas of one hundredth of the evaporation pan area. It is subdivided into 20 equal divisions each of which equal to 0.20mm of water in the pan. The water level in the evaporation pan is set at the reference point and after 24 hours, the enough water is added by the measuring tube, back to original level at the apex of fixed point gauge. The amount of water needed to bring the water back to the original level is equivalent to the amount of water loss through evaporation. In the automatic measurement method, the recoding process can be automated by electronically measuring the rate of change of water height. An ultrasonic Doppler depth sensor housed inside a stilling well would measure the height of water in the evaporation pan. The sensor installed at about 3.5 cm above the water level in the evaporation pan. In the ruler scale and float pointer measuring instrument, the ruler scale with floating indicator are installed with evaporation pan. A pointer is moving over the ruler scale due to the reduction in the water level.

3.0 Empirical Equation to Estimate Evaporation

The empirical equations such as Dalton-based formula, Meyer's formula and Rohwer's formula are developed based on experimental data and boundary condition [13].

3.1 Dalton's Evaporation Formula

In the Dalton's Evaporation formula Evaporation rate (E) depends on the wind speed correction factor$\left(f(u)\right)$, saturate $\left(e_{pw}\right)$ and actual vapor pressure$\left(e_{pa}\right)$.

$$E = kf(u)\left(e_{pw} - e_{pa}\right) \quad (3)$$

In this the equation, the challenging issue is to determine the wind speed correction function which is a major drawback to use this equation**.**

3.2 Meyer's Evaporation Formula

This equation is a modified form of Dalton's evaporation formula to determine the lake evaporation(E_l). In this equation monthly mean wind velocity(U_9) above 9 m from ground level and a coefficient (k_m) accounting 0.36 for large deep water and 0.050 for small shallow lake are introduced.

$$E_l = k_m\left(e_{pw} - e_{pa}\right)\left(1 + \frac{U_9}{16}\right) \quad (4)$$

3.3 Rohwer's Evaporation Formula

This equation is developed to calculate evaporation of large pool or lake and is also developed form of Dalton's evaporation formula, incorporated with mean barometric pressure (P_a) and wind speed effect.

$$E_l = (1.132 - 0.00054P_a)(0.44 + 0.07U_0)\left(e_{pw} - e_{pa}\right) \quad (5)$$

4.0 Analytical Method to Estimate Evaporation

Water balance, Energy balance and combination of water and energy balance methods are used to estimate evaporation from evaporation pan.

4.1 Water Balance Method

In this method, evaporation is calculated from changes in the volume of water in evaporation pan. Therefore, the evaporation(E) depends on water in $(I)$and out (O) flow, surface seepage losses (S_l) and change in water storage (S). The main challenge in this method is measurement accuracy.

$$E = I - O - S - S_l \quad (6)$$

4.2 Energy Balance Method

In this method, the evaporation from a water body is estimated at the energy component required for evaporating water from the reservoirs. Fig. 5 shows the energy component during evaporation from pan.

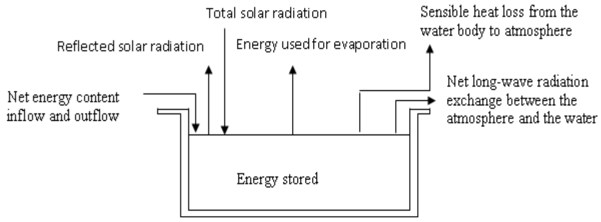

Fig. 5: Water Body Energy Balance during Evaporation

According to the energy balance method, the net radiation absorbed by water body $(Q_n)$and the net energy content of inflow and outflow elements (Q_v) is same as sum of the energy use for evaporation (Q_e), sensible heat transfer (Q_h) and amount of energy change in pan water (Q_t).

$$Q_n + Q_v = Q_h + Q_e + Q_t \quad (7)$$

Sensible heat transfer of the atmosphere is difficult to measure for the reason that the amount of air mass heat gain from water reservoirs is unknown and it is different in different location of atmosphere. If the sensible heat transfer(Q_h) to air from water is function of humidity(R) and water evaporation(Q_e). Then sensible heat, humidity and daily evaporation can be determine by using the equations

$$Q_h \approx R \times Q_e \quad (8)$$

$$R = \gamma \frac{T_w - T_a}{e_{pw} - e_{pa}} \quad (9)$$

$$E = \frac{Q_e}{\rho L_e} \quad (10)$$

Where,T_a and T_w are air and water surface temperature in °C and $e_{pa}$and e_{pw} are air and saturated vapor pressure; γ is the psychometric constant and L_e is the latent heat of evaporation. Therefore the energy balance can be simplified as

$$E = \frac{Q_n + Q_v - Q_t}{\rho L_e(1 + R)} \quad (11)$$

4.3 Combination method

A combined method is the modification of the energy method. Evaporation may be occurring by the aerodynamic method at what times the energy supply is not limiting, and by the energy balance method when the vapor transport is not limiting. Equation 12 is based on a combination of aerodynamic and energy balance equations [11].

$$E = \frac{mR_n + \rho c_p E_r}{L_e(\gamma + m)} \quad (12)$$

where, m is the slope of the saturation vapor pressure versus temperature curve at the air temperature in $\mathrm{P_a/k}$, R_n is the net irradiance in $\mathrm{W/m^2}$, and E_r is the parameter including wind speed and saturated vapor pressure deficit in $P_a m/s$. The value of m can be determined from the empirical shown in equation 13 and 14.

$$m = 0.04145e^{-0.06088T} \quad (13)$$

$$m = \left\{4098 \times \left(\frac{0.6108e^{\frac{27.27T}{T+237.3}}}{(T + 237.3)^2}\right)\right\} \quad (14)$$

For long wave radiation, net long wave radiation is equal to the long wave flux coming from the atmosphere, minus the amount of reflected from the surface and the amount radiated from the surface [12]. Mathematically

$$R_n = \varepsilon_w \varepsilon_{at} \sigma {T_a}^4 - \varepsilon_w \sigma {T_s}^4 \quad (15)$$

Where, ε_w and ε_{at} are water and effective emissivity which is a function of humidity and cloud cover in sky. The average value of the effective emissivity is 0.98.

Consider the incident solar radiation outside the atmosphere on a horizontal surface. The net irradiance (R_n) is the different between incoming and reflection radiation(R_l) [14]. The amount of coming radiation on water body can be determined from the equation 16.

$$R_i = R_A(1 - r)\left(a + b\frac{n}{D}\right) \quad (16)$$

Where, R_A is the total possible radiation for the period of estimation, it is function of latitude and season; r is the reflection coefficient (albedo) varies $0.05 \sim 0.12$; a is a constant depending upon the latitude $0.29\cos\phi$ where ϕ is the latitude; b is a coefficient an average value 0.5; and n/D is the fraction of possible sunshine from climatic atlas. The net back radiation flow from water surface is calculated from equation 17.

$$R_l = \sigma T^4\left(0.56 - 0.092\sqrt{e_{ap}}\right)\left(0.1 + 0.9\frac{n}{D}\right) \quad (17)$$

Where, σ is Stefan-Boltzmann constant 2.01×10^{-9} mm/day. In the equation 12, the psychrometric constant (γ) is the function of air pressure and ratio of molecular weight of air to water. So the equation 12 becomes

$$E_{mass} = \frac{mR_n + \rho c_p(1 - 0.01RH)e_w g_a}{\lambda(\gamma + m)} \quad (18)$$

5.0 Comparison of Evaporation in Different Methods

After comparing it is found that analytical methods can provide good results. They involve parameters that are difficult to assess. Empirical equations can at best give approximate values of the correct order for magnitude. In view of the above, pan measurements find wide acceptance in practice.

6.0 Effect of Concentration on Evaporation

Fick's law of diffusion states that the mass diffusion flux has an inverse relationship to the solute concentration [12]. Mathematically,

$$m_A = -\rho D_{AB} \nabla m f_A \quad (19)$$

Where, m_A is mass flux; $D_{AB}$is binary diffusion coefficient, C_A is concentration of species A and $\Delta m f_A$ is mass fraction of species A. Study showed that the rate of evaporation from sea water is about 2-3% less than from fresh water because of concentration difference [15].

6.1 Effect of Algae on Evaporation

A large amount of algae is present in the evaporation pan which increases the density of solution in the pan. According to the Fick's law, the density of the solution or liquid is higher due to solute or suspended solids, so rate of evaporation must be slower. In terms of energy consumption of a fresh water pond, the net solar energy is used for evaporating the water only. Other than in an algae cultivation pond, net solar energy is used for both the water evaporation and physiological function of algae (Osmosis and photosynthesis). Algae containing nutrients and in general, nutrient-like substances that dissolve in water tend to slightly decrease water's evaporation rate. Therefore, it can be thought that algae cultivation in the pond will reduce the evaporation rate.

7.0 Summary of Factors Affecting Evaporation

Evaporation is a function of climatic and environmental conditions and it is influenced by different factors. The factors are

- The lowest evaporation rate is found in winter season where as the highest in either monsoon or pre monsoon season.
- The evaporation rate is found slower when the solute concentration in a liquid is higher.
- The evaporation of water reduces with increasing reflectance of solar irradiance from the water surface. The change of reflectance of solar energy is required a surface modification.
- The evaporation rate is increased with increased vapor pressure deficit.
- Higher vapor pressure deficit means the lower relative humidity.
- Air temperature is one of the principal factors causing evaporation.
- The flow of less saturated air leads increased evaporation rate. A natural draft chimney above the pond can be used to artificially increase air evaporation rate.
- At higher elevations, the atmospheric pressure is less than at a lower altitude. At a lower atmospheric pressure, it is easier for a liquid to evaporate.

- The rate of evaporation increases with water temperature however, the evaporation rate might be lower at another location with the same average temperature due to a higher relative humidity. Water temperature can be controlled by using a suitable insulator on the outer surface of the evaporation pan.
- The net result is a decrease in evaporation that is more or less proportional to the decrease in temperature.
- The large surface area has more surface molecules that are able to escape easily as a result the rate of evaporation is faster than the same volume of water but has a smaller surface area.
- The building is a resistor to wind movement. The air direction and speed can be changed by the building as a result evaporation rate will be slower.

4. 1 Conclusion

Evaporation is an important factor that influences cultivation and harvesting of algae. The amount of water that must be refilled into the algae cultivation pond annually is equal to the loss by evaporation. By algae cultivation, the farmer should gain the right knowledge of the evaporation characteristic in algae culture ponds and also should estimate the amount of water to be lost through evaporation.

Dewatering algae by the natural convection method included draft enhancement of installing a wire mesh on the chimney may be a higher expectable novel technology which is to promise zero-energy input. The rate of dewatering algae for the convection dewatering will be measured by the evaporation rate. The measurement of evaporation rates entails the measurement of water volume reduction in evaporation over a period of time.

It can be predicted by using water balance, energy balance, combination energy and water balance or Penman equation. Selection of a suitable evaporation measurement method depends on the character of the water reservoir and the surrounding aerodynamic condition. The combination of mass and energy transfer balance or Penman equation will yield higher accuracy of the result but the measurements of its variables are difficult. The pan measurement method is simple to compare with other evaporation rate measurement methods. In the pan measurement method, the pan has a constant surface area; therefore the water volume reduction is only the function of water depth of the evaporation pan. The accuracy of pan evaporation results depends on the pan size and shape, pan materials and place of installations of the pan.

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