Determination of Mass Transfer Coefficient for Evaporation Water from Surface of Swimming Pool and Amount of Water Loss per Day

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Abstract— The calculation of evaporation is required from a variety of water pools including swimming pools, water storage tanks and vessels, spent fuel pools in nuclear power plants, etc. In reality, evaporation is a very complex process that is difficult to estimate using equations. This is because the rate of evaporation is actually controlled by many factors including, temperature, air pressure, wind speed, and humidity. Several equations exist that can be used to predict evaporation. The purpose of this brief paper is to describe some principles involved in estimating evaporation with example data from large and small water bodies. Particular emphasis will be on practical procedures and techniques that professionals can use to estimate evaporation from shallow water bodies using pan evaporation and a combination equation using available weather data and/or new data collected specifically for estimating daily evaporation.

Key words: EPA Evaporation, Water Loss

I. INTRODUCTION

Because of nature, evaporation from water surfaces is rarely measured directly, except over relatively small spatial and temporal scales (Jones 1992)[1]. Evaporation from water is most commonly computed indirectly by one or more techniques. These include pan coefficients × measured pan evaporation, water balance, energy balance, mass transfer, and combination techniques. The selection of the "best" technique to use for a particular computation is largely a function of the data availability, type or size of the water body, and the required accuracy of the estimated evaporation. The most commonly used method in the US for estimating evaporation from small, shallow water bodies, is to measure evaporation from a standard pan and then multiply by a coefficient. Hence it is necessary to measure the rate of evaporation and evaporation water from the surface of the swimming pool.

II. BACKGROUND

Background Theories of evaporation from water surfaces go back to at least the 8th century B.C., but measurement and experimentation go back to the 17th and 18th centuries. Brutsaert (1982)[2] credits Dalton's 1802 paper (cited by Brutsaert 1982, p. 31)[2] as a major event in the development of evaporation theory. He expressed Dalton's results in present day notation as E =f(ū)(e₀ – e_a) where E is the rate of evaporation expressed as rate per unit time, ū is mean wind speed, e_o is the saturation vapour pressure at the temperature of the water surface and e_a is the vapour pressure of the air. Evaporation requires energy, the primary source being solar radiation. Bowen (1926)[10] developed what is now known as the Bowen ratio (BR). It is the ratio of heat loss by conduction to that by evaporation, or Δt/Δe, the ratio of air temperature gradient to vapour pressure gradient above the surface. The BR has had a major impact on methods of estimating and measuring evaporation technologies. McEwen (1930)[3] described evaporation as a transformation of energy based on earlier work of Bowen (1926) and Cummings and Richardson (1927)[7]. Many US states have tabulated evaporation data measured with evaporation pans. Some states have computed state-wide estimates of evaporation from shallow ponds and reservoirs (Borrelli et al. 1998)[10]. Many early studies and reports have also addressed pan evaporation

III. MECHANISM OF EVAPORATION

Consider evaporation from an undisturbed water surface, such as that of an unoccupied swimming pool. A very thin layer of air, which is in contact with water, quickly gets saturated due to molecular movement at the air-water interface. If there is no air movement at all, further evaporation proceeds entirely by molecular diffusion, which is a very slow process. On the other hand, if there is air movement, this thin layer of saturated air is carried away and is replaced by the comparatively dry room air and evaporation proceeds rapidly. Thus, it is clear that for any significant amount of evaporation to occur, air movement is essential. Air movement can occur due to two mechanisms: 1. Air currents caused by the building ventilation system for indoor pools and wind for outdoor pools. This is the forced convection mechanism. 2. Air currents caused by natural convection (buoyancy effect). Room air in contact with the water surface gets saturated and thus becomes lighter compared to the room air, and therefore moves upwards. The heavier and drier room air moves downwards to replace it. For outdoor swimming pools, forced convection is usually the prevalent mechanism. For indoor pools, natural convection mechanism usually prevails while most published formulas have considered only forced convection.

A. US EPA Evaporation Equation

The EPA Evaporation equation was developed to estimate evaporation from the surface of a pool of liquid that is at or near ambient temperature.

$$E = \frac{7.4PA(0.447W)^{0.78}}{T + 459.67}$$

Where
- E = Evaporation Rate (Gallons/Day)
- A = Pool Surface Area (ft²)
- W = Wind Speed Above Pool (mph)
- P = Water's Vapor Pressure (mm of Hg) at Ambient Temperature
- T = Temperature (°F)

B. Stiver and Mackay Evaporation Equation

The following equation was developed by Warren Stiver and Dennis Mackay of the Chemical Engineering Department at the University of Toronto. It can be used to estimate evaporation from the surface of a pool of liquid that is at or near ambient temperature.

$$E = \frac{PAW}{T + 459.67}$$

Where

- E = Evaporation Rate (Gallons/Day)
- A = Pool Surface Area (ft^2)
- W = Wind Speed Above Pool (mph)
- P = Water's Vapor Pressure (mm of Hg) at Ambient Temperature
- T = Temperature (°F)

C. John W. Lund Evaporation Equation

In 2000, John Lund working at the Oregon Institute of Technology developed the following equation specifically for determining evaporation in swimming pools.

$$E = 0.0306AF_a(P - P_a)$$

Where:

- E = Evaporation Rate (Gallons/Day)
- A = Pool Surface Area (ft^2)
- F = Activity Factor (See Table at Right)
- P = Water's Vapor Pressure (mm of Hg) at Ambient Temperature
- P_a = Water's Vapor Pressure (mm of Hg) at Dew Point Temperature

The saturation vapor pressure value should correspond to the water's surface temperature and can be pulled from the table referenced in the first equation. This equation assumes a constant wind current of 0.22mph (0.1 meters/sec) over the pool's surface.

IV. ENERGY CONSIDERATIONS

Incoming solar radiation is the principle source of energy for evaporation. Although calculation of net radiation for land and water surfaces is similar, there is one major difference. For land surfaces, the net solar radiation (incoming solar radiation minus reflected solar radiation) is converted to sensible and latent heat at the soil or plant surfaces. In contrast, net solar radiation is not all absorbed at the water surface. Part of net solar radiation may penetrate to great depths in clear water. The depth of penetration varies with wave length. In pure water, about 70% of the solar radiation adsorption occurs in the top 5 m. Solar radiation adsorbed below the water surface is stored as energy and is not immediately available for evaporation or for sensible heat. Stored energy typically results in a lag of evaporation relative to net solar radiation, and there usually is less total annual evaporation than when there is no significant energy storage. As the solar intensity begins to decrease after about mid July, the stored energy gradually becomes available for evaporation and sensible heat loss. For shallow water bodies, the amount of energy stored during the rising and falling solar cycle may not be large, but usually is large enough to affect daily evaporation rates. The heat exchange with the surroundings includes the following:

- Heat flow rate by evaporation
- Heat flow rate by convection
- Heat flow rate by short-wave radiation
- Heat flow rate by long-wave radiation
- Heat loss by fresh water supply
- Heat flow rate from heating
- Thermal conduction to the ground

V. PROBLEM DESCRIPTION

Swimming pool dimensions are shown in Fig. 1.

- Length - 15m
- Breadth - 5m
- Relative humidity – 40%
- Ambient Temperature - 27°c
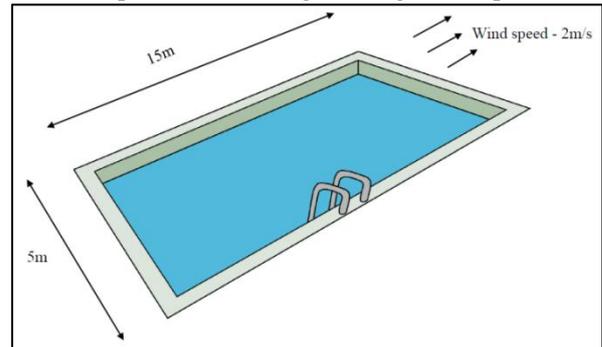- Wind Speed – 2m/s along the long side of pool.

Fig. 1: Swimming pool dimensions

A. Determination of Mass Transfer Coefficient

The various thermo physical properties of air and water are taken from the Heat and Mass Transfer table.

From tables,

Kinematic viscosity (υ) of air = 15.89×10^{-6} m^2/s.

Saturated water vapour at 27^0C

$$\rho_{A\,sat} = \frac{1}{\upsilon g} = \frac{1}{22.93} = 0.0436 \text{ kg/m}^3$$

From water vapour – air table,

$$D_{AB} = 0.26 \times 10^{-4} \text{ m}^2/s$$

$$Sc = \frac{\gamma}{Dab} = 0.61$$

$$Re = \frac{\mu\infty}{\upsilon} = \frac{2 \times 15}{15.89 \times 10 - 6} = 18.88 \times 10^5 \text{ (turbulent)}$$

Assuming the transition takes place at $Re_{x,\ c} = 5 \times 10^5$,

The point where it occurs is at

$$X_c = (5 \times 15 \times 10^5) / (18.88 \times 10^5) = 3.97m.$$

Thus mixed layer boundary layer exists.

$$Sh_L = (0.037Re_L^{4/5} - 870) \, Sc^{1/3} = ((0.037)(18.88 \times 10^5)^{4/5} - 870)(0.61)^{1/3} = 2553.$$

$$H_{ml} = Sh_L \frac{Dab}{L} = 2553(0.26 \times 10^{-4})/15 = 4.4 \times 10^{-3} m/s$$

B. Rate of Evaporation

Mass transfer coefficient = 4.4×10^{-3} m/s

Partial pressure of water vapour at water surface at 27^0C

$$P_{SAT} \text{ at } 27^0C = 3531 \text{ N/m}^2$$

Saturation pressure of water vapour in air at 27^0C and 40% RH

$$P_\infty = 0.4 \times 6221 = 2488.4 \text{ N/m}^2$$

Total pressure of air = $P_w + P_a = 101.325 \times 10^3$ N/m^2

$$C = \frac{P}{RT}$$

$$\rho = MC = \frac{MP}{RT}$$

$$\rho = \frac{Mw\ Psat}{R\ Tw} = \frac{(18)(3531)}{(8361)(300)} = 0.024576\ \text{kg/m}^3$$

$$\rho_{a\infty} = \frac{Ma\ P\infty}{R\ T\infty} = \frac{(18)(2488.4)}{(8316)(310)} = 0.01737\ \text{kg/m}$$

Rate of evaporation of water is

$$N_A = h_m(\rho_{as} - \rho_{a\infty})$$

$$= (4.4 \times 10^{-3})\ (0.025476 - 0.01737)\ (3600)\ (24)$$

$$= 3.081\ \text{kg/m}^2$$

Water loss from pool area of 5×15 m^2 is

$$= 3.081 \times 5 \times 15 = 231.1\ \text{kg/day}.$$

VI. CONCLUSION

Evaporation is rarely measured directly, even in small water bodies. It is usually estimated by association with measured evaporation from evaporation pans or calculated by water balance, energy balance, mass transfer or a combination of energy balance and aerodynamic techniques. The method selected depends on the depth of the water body and the availability of weather data. The present research is carried out for the small swimming pool to determine the Mass transfer coefficient and rate of evaporation of water per day.

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