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Improved method for calculating evaporation from indoor water pools

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ABSTRACT

The author had earlier published a formula for calculating evaporation from unoccupied indoor swimming pools and other water pools. The formula was derived from the analogy between heat and mass transfer during natural convection. It was shown to be in good agreement with all published test data. However, it was applicable only to positive density difference (i.e. when the density of room air was greater than that of air at the pool surface). The methodology has now been extended to apply to negative density differences. The extended calculation method has been validated with all available test data. This paper presents the improved method and its comparison with data from eleven sources. All data are predicted with a mean deviation of 14.5%. Thus this method can be confidently used for swimming pools as well as other pools with quiet water surface.

1. Introduction

Accurate calculation of evaporation from swimming pools is needed to ensure proper sizing of HVAC equipment as well as for the estimation of energy consumption. Numerous empirical correlations have been presented for unoccupied swimming pools, the best known among which is the correlation of Carrier [1]. None of them has been found to be accurate beyond the data on which they were based [2]. ASHRAE Handbook [3] has provided multiplication factors (called activity factors) to be applied to the Carrier correlation to bring predictions closer to those experienced. However, attempts at such corrections cannot be fully successful as evaporation occurs mainly by natural convection while the Carrier formula does not include the parameters to take it into account. As was shown by Shah [2,4], it shows poor agreement with data for unoccupied pools.

The present author presented a formula for evaporation from an undisturbed water pool into quiet air derived by the direct application of the analogy between heat and mass transfer [2,4]. It was shown to be in good agreement with almost all available test data. However, it is applicable only to positive air density difference (i.e. when the density of room air is larger than the density of air at the surface of water). There are situations in which the density difference is negative. The calculation methodology has now been extended to include such situations.

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In the following, the further development of the author's formula to extend it to negative density differences and forced air flow is presented.

2. ASHRAE handbook method of calculation

The ASHRAE method is based on the following formula given by Carrier [1]:

$$E = \frac{(0.089 + 0.0782V)(p_w - p_r)}{i_{fg}} \tag{1}$$

This formula was based on tests done on an unoccupied pool across which air was blown. In the past, it was widely used for both occupied and unoccupied pools with or without forced air flow. Experience showed that it greatly over-predicted evaporation from unoccupied pools as well as from some occupied pools. ASHRAE Handbook [3] therefore gave the multipliers (called activity factors) to correct the predictions of Eq. (1). For unoccupied pools, the activity factor is 0.5. Further, Eq. (1) is modified in ASHRAE Handbook [3] to the following form which is recommended for air velocities between 0.05 and 0.15 m/s.

$$E = 0.000144(p_w - p_r) \tag{2}$$

3. Shah formula for unoccupied pools

By the use of the analogy between heat and mass transfer during natural convection, Shah [2,4] derived the following formula for evaporation from unoccupied pools.

$$E = 35\rho_w(\rho_r - \rho_w)^{1/3}(W_w - W_r) \tag{3}$$

Nomenclature

E	rate of evaporation from (kg/m^2 h)
i_{fg}	latent heat of vaporization of water (kJ/kg)
h_M	mass transfer coefficient (m/h)
p	partial pressure of water vapor in air (Pa)
V	air velocity (m/h)
W	specific humidity of air (kg of moisture/kg of air)
ρ	density of air, mass of dry air per unit volume of moist air (kg/m^3)

Subscripts

w	saturated at water surface temperature
r	at room temperature and humidity

For $(\rho_r - \rho_w) < 0.02$, predictions were found to be somewhat low. This was attributed to stray air currents and edge effects which become significant as the natural convection currents become weak. To account for these effects, a 15% increase in E was specified for $(\rho_r - \rho_w) < 0.02$.

This formula was found to be in good agreement with virtually all published data for field and laboratory tests. The shortcoming is that it cannot make any prediction when $(\rho_r - \rho_w) \leq 0$. This shortcoming has been remedied in the further development discussed in the next section.

4. Further development for pools with typical ventilation systems

4.1. Physical model

Evaporation occurs by two mechanisms:

- Natural convection
- Convection due to air currents caused by ventilation system

Various models for interaction between the two mechanisms have been proposed. Here it is postulated, subject to validation with test data, that these two mechanisms work independent of each other and all evaporation occurs by the stronger of the two mechanisms.

4.2. Evaporation by natural convection

Air in contact with the surface of water becomes saturated with air, thus becomes lighter, and moves upwards carrying the evaporated water with it. The heavier and drier room air moves down to take its place and this cycle continues. Eq. (3) gives the evaporation due to this effect.

4.3. Evaporation due to air flow by ventilation system

Typical ventilation systems consist of supply diffusers on the ceiling near the wall on one side of the pool and return diffusers on the opposite side of pool. These produce air movement over the pool.

When the density of air at the pool surface is greater than the density of room air, natural convection essentially ceases. Then essentially all evaporation will be due to these ventilating air currents. Thus by analyzing the data at negative density differences, the formula for evaporation due to air currents can be found.

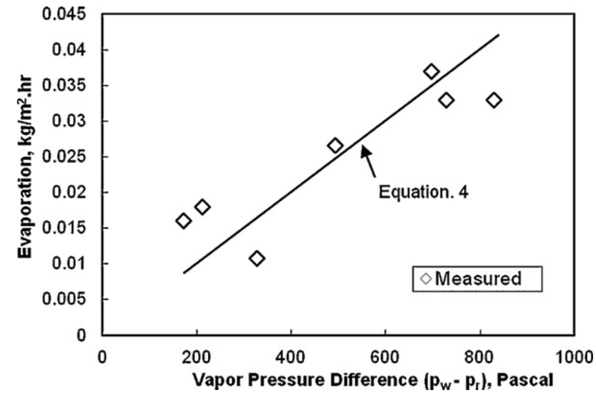

Fig. 1. Analysis of data for negative density difference, i.e. $(\rho_a - \rho_w) < 0$.

The available data for negative density difference are plotted in Fig. 1. The following equation is fitted to these data.

$$E = 0.00005(p_w - p_r) \tag{4}$$

This is the formula for evaporation due to forced convection due to air movements produced by the ventilation system.

4.4. Calculation procedure

Calculate evaporation by Eqs. (3) and (4). Use the larger of the two. This is the evaporation rate from unoccupied pools.

4.5. Discussion on Eq. (4)

Rate of evaporation can be expressed by the following equation [5]:

$$E = \frac{h_M}{RT}(p_w - p_r) \tag{5}$$

Changes in the absolute air temperature T are insignificant and R is the gas constant. As the variations in fluid properties will be small, the mass transfer coefficient h_M essentially depends only on the air velocity. Thus:

$$E = C.\ \text{function}(V)(p_w - p_r) \tag{6}$$

where C is a constant and V is the air velocity.

Air velocity over pool is not uniform like that produced by wind on outdoor pools. The air flow patterns are complex, with air velocity and direction varying along all three axes. This can be seen in Li and Heisenberg [6] who performed a CFD simulation of a public swimming pool. They compared the measured air temperature and humidity at the return grilles with the model prediction and found excellent agreement; hence their CFD model can be considered reliable. Their model used the Shah formula [2] to predict evaporation rate. Most of the local air velocities were in the range of near zero to 0.2 m/s but there were also higher velocities.

Smith et al. [7] measured air velocity above a large indoor public swimming pool. The velocity varied from 0.035 to 0.05 m/s. Hanssen and Mathisen [8] measured velocity above the surface of a public pool. They noted that the velocity was very unsteady and varied from point to point. They found it to average 0.15 m/s. The difference in velocities measured by Smith et al. and Hanssen and Mathisen is understandable considering the wide variations of velocities found in the CFD simulation of Li and Heisenberg [6]. ASHRAE Handbook recommends Eq. (2) for velocities of 0.05–0.15 m/s. Thus there is a reasonable agreement in the range of velocities occurring in swimming pools.

With such complex air flow patterns, the mass transfer coefficient cannot be calculated with equations for forced flow over a flat