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Prediction of evaporation from occupied indoor swimming pools

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Abstract

Reliable methods for the prediction of evaporation from occupied indoor pools are needed for sizing the air conditioning equipment and for energy consumption calculations. No well-verified method of prediction is available at the present. Two new correlations are presented here. One is based on the analysis of physical phenomena and the other is purely empirical. A literature survey was done to collect test data from occupied indoor pools. Analyzable data were found from four sources. These include pool areas from 64 to 1209 m^2, occupancy from 64 to 3 m^2 per person, water temperature from 25 to 30 °C, air temperatures from 26 to 32 °C, and relative humidity from 32 to 72%. These data were compared to the new correlations as well as the existing correlations. The new empirical correlation performed best with a mean deviation of 16.2%. The next best was the new phenomenological correlation with a mean deviation of 26.2%. The Carrier correlation performed well at high occupancies. The new correlations provide reliable methods for predicting evaporation from occupied pools and will be useful in design and analysis.

Keywords: Evaporation; Swimming pools; Correlations; Prediction

1. Introduction

Reliable calculation of evaporation from swimming pools is needed for sizing the air conditioning equipment as well as for energy consumption calculations. Underestimation of evaporation will lead to selection of undersized air conditioning equipment, resulting in excessive humidity that can cause discomfort to the occupant and damage to the building from fungus and rot. An overestimate will result in the selection of oversized equipment with high cost, excessive energy consumption, and operating problems due to too much cycling.

The present author recently compared the available correlations and data for unoccupied pools and made recommendations for calculation of evaporation from unoccupied pools [1]. However, these recommendations are not applicable to occupied swimming pools as it is well known that evaporation from occupied pools is much higher than that from unoccupied pools; see for example Doering [2]. While some methods for predicting evaporation from occupied pools have been published, none of them has been compared with data from several sources.

It is clear from the above that no well-verified method for the calculation of evaporation is available while there is need for it. The research reported in this paper was done to fulfill this need. Literature survey was done to find test data and predictive techniques. Two new correlations were developed, one based on consideration of physical phenomena and the other empirical. The existing as well as the new correlations were compared with all available data.

In the following, the test data and physical phenomena are discussed, the existing and the new correlations are presented, and the results of comparison with data are presented and discussed.

2. Test data

Intense efforts were made to collect test data for evaporation from occupied indoor swimming pools. Five sources of test data were found. Among these, the data of Reeker [3] are not analyzable as the details needed for this purpose are not given. Analyzable data were found from four sources and these are summarized in Table 1. These data are discussed in the following.

Smith et al. [4] estimated the rate of evaporation through an energy balance on the water in the pool. Essentially, evaporation was attributed entirely to the difference between the total energy supplied to the water and the sensible heat gained by water. Evaporation from the wet deck and from the

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Nomenclature

A_{bodies}	surface area of portion of bodies of pool occupants exposed to air (m^2)
A_{max}	maximum area of pool per occupant at full occupancy (4.5 m^2/person)
A_{pool}	surface area of pool (m^2)
A_{spray}	contact area between air and water spray (m^2)
A_{waves}	additonal water surface area due to waves in pool (m^2)
A_{wetdeck}	area of wet portion of pool deck (m^2)
E	rate of evaporation at actual occupancy (kg/m^2 h)
E_0	rate of evaporation from unoccupied pool (kg/m^2h)
E_R	E/E_0
F_u	pool utilization factor, defined by Eq. (6)
i_{fg}	latent heat of vaporization of water (kJ/kg)
N	number of occupants
p	partial pressure of water in air (Pa)
Δp	$p_w - p_r$
W	specific humidity of air (kg of moisture/kg of dry air)
Greek letters	
η	number of data points
ρ	density of air (kg/m^3)
$\Delta\rho$	$\rho_r - \rho_w$
Subscripts	
w	saturated at water surface temperature
r	at room temperature and humidity

wet bodies of the swimmers were not considered while these can be significant as will be evident from the discussion on physical phenomena later in this paper.

All other researchers listed in Table 1 measured the amount of condensate collected at the cooling coil of the air conditioning unit and assumed that this was equal to the amount of water evaporated from the pool surface. The amount of condensate collected is affected by infiltration of air; it can be higher or lower than the actual evaporation depending on whether the outside humidity is higher or lower than that in the room. If a pool is in use, infiltration will be high as the door openings will be frequent with users walking in and out of the facility.

In some cases, the same air conditioner also served the shower rooms. Thus, the water evaporated from the showers will also have condensed at the air conditioner's coil. Biasin and Krumme [5] did some measurements of evaporation from showers. These indicate that this amount is rather small and hence will not have substantially affected the reported evaporation rates.

Smith et al. [4] state that during their tests, a number of activities occurred at the same time, including swimming, diving, and aquatic exercise. This is usually the case in public pools and this may be regarded as normal activity. The other data analyzed here also appear to be for similar activity.

3. Correlations for unoccupied pools

In order to understand the physical phenomena causing the evaporation in occupied pools being higher than in unoccupied pools, it is necessary to look at the equations for predicting evaporation in unoccupied pools. The present author listed the available correlations in an earlier paper [1]. Most of them are empirical equations of the form:

$$E = \gamma A_{\text{pool}}(\Delta p)^n \tag{1}$$

where A_{pool} is the pool surface area, γ a constant, and n varies from 1 to 1.2.

The following formula based on the analogy between heat and mass transfer has been given by the present author in earlier papers [1,6]:

$$E = K\cancel{A}_{\text{pool}}\rho_w(\rho_r - \rho_w)^{1/3}(W_w - W_r) \tag{2}$$

where K is a constant defined as

$$K = 35, \quad \text{for } (\rho_r - \rho_w) > 0.02$$

$$K = 40, \quad \text{for } (\rho_r - \rho_w) < 0.02.$$

The density ρ is in kg/m^3. If $\rho_r - \rho_w$ is negative, its absolute value is used.

According to both of the above equations, evaporation increases as the pool area increases, in other words as the area of contact between water and air increases. Thus, any physical phenomenon increasing the area of contact between air and water will increase the rate of evaporation.

According to Eq. (1), evaporation increases with increase in p_w which increases with increasing water temperature. According to Eq. (2), evaporation increases with increasing W_w and decreasing ρ_w; these occur as water temperature increases. Thus, both these formulae indicate that evaporation will increase with increasing water temperature.

4. Physical phenomena

The following physical phenomena occur in occupied pools.

- *Waves on water surface*: Presence of even a single swimmer causes waves on the pool surface thus increasing the surface area of water in contact with air.
- *Wet deck*: Splashing and drip from the swimmers walking around the deck result in the deck becoming wet and thus increase in the water surface area in contact with air. The area of deck is often comparable to that of the pool. With a large number of occupants, much of the deck can become wet.

Table 1
Published data on measurement of evaporation from active swimming pools

Researcher	Pool area (m^2)	Air temperature (°C)	Air rel. humid. (%)	Water temperature (°C)	F_u	Maximum no. of persons	Evaporation measuring method	Notes
Doering [2]	425	27.5 29.0	33 41	25.0	0.11 0.75	71	Measurement of condensate from air conditioning unit	
Biasin and Krumme [5]	64	26.0 31.7	46 72	26.0 30.0	0.07 0.65	8		Condensate included evaporation from showers
Heimann and Rink [7]	200	31.0	54 55	28.5	0.45 1.46	65		
Smith et al. [4]	1209	29.4	50	26.7 27.8	0.05 0.64	180	Energy balance on pool water	
All data	64 1209	26.0 31.7	33 72	25.0 30.0	0.05 1.46	8 180		

- *Wet bodies of occupants*: The wet bodies of swimmers exposed to air provide additional area of contact between air and water. As the body temperature is considerably higher than that of pool water, the rate of evaporation from bodies is higher than from the pool surface.
- *Sprays caused by activity*: Sprays of water droplets are caused by active occupants, their extent increasing with activity. Novice swimmers cause considerable sprays. Diving and sports such as water polo cause intense sprays. The sprays contain water droplets which offer a large amount of surface area in contact with air.

5. Derivation of a phenomenological correlation

All the phenomena discussed above tend to increase evaporation by increasing the air–water interface area and thereby increase evaporation. However, the increase in evaporation may not be in direct proportion to the increased area in the case of wet deck and wet bodies. The temperature of water on deck may be higher or lower than the pool temperature; it is not possible to make a generalization. The pool water temperature is almost always much lower than the body temperature. Hence, the rate of evaporation from bodies will tend to be faster than from the pool surface.

As a first approximation, the temperature variations are ignored and it is assumed that the entire increase in evaporation during occupancy is due to the increase in the interface area. Then,

$$E_R = \frac{A_{\text{pool}} + A_{\text{wetdeck}} + A_{\text{bodies}} + A_{\text{waves}} + A_{\text{spray}}}{A_{\text{pool}}} \qquad (3)$$

where

$$E_R = \frac{E}{E_0} \qquad (4)$$

where E_0 is the rate of evaporation from unoccupied pools.

To estimate the area of wet deck, let us first assume that the area of the deck is equal to the pool area; this is a good approximation in many cases. It is further assumed that the wetting of deck increases linearly with occupancy until it is completely wet at full occupancy. Thus,

$$A_{\text{wetdeck}} = F_u A_{\text{pool}} \qquad (5)$$

where F_u is the pool utilization factor defined as

$$F_u = \frac{A_{\max}}{A_{\text{pool}}/N}. \qquad (6)$$

where N is the number of occupants, and $A_{\max}$ the pool area per person at maximum occupancy. Biasin and Krumme [5] have given figures from German standards according to which $A_{\max}$ is almost constant at 4.5 m^2 per person for ordinary swimming pools. This value is used in further discussions in this paper.

The body area of adults varies from 1.4 to 1.9 m^2. Some of the occupants may be children, some may be standing in the water, some may be out on the deck, some may be swimming, and so on. As it is not possible to predict these details, the average body area exposed to air per occupant is approximately taken to be 1.4 m^2. With $A_{\max} = 4.5\ m^2$,

$$A_{\text{bodies}} = 0.3 F_u A_{\text{pool}}. \qquad (7)$$

Smith et al. [4] estimated that the waves increased pool area by about 20%, with waves 150 mm high at 900 mm intervals. Using this estimate, for $F_u > 0$:

$$A_{\text{waves}} = 0.2 A_{\text{pool}}. \qquad (8)$$

The contribution due to sprays is likely to be important during sports and diving. For normal pool usage, spray is not likely to be a major contributor. As a first approximation, it is neglected.

Substituting Eqs. (5)–(8) in Eq. (3), the following relation is obtained:

$$E_R = 1.3F_u + 1.2. \tag{9}$$

This will obviously apply only at $F_u > 0$ as there are no waves or wet deck at zero occupancy. Further, increases in F_u beyond 1 will not increase E_R as the deck is already fully wet at $F_u = 1$ according to the assumption on which Eq. (5) is based and the activity level will decrease with increasing occupancy as the occupants will be cramped for space. This leveling off of evaporation at very high occupancies is seen in the data of Heimann and Rink [7] and has also been noted by Smith et al. [4]. Thus, we may say that Eq. (9) is applicable for F_u between say 0.1 and 1. For $F_u > 1$, use the value for $F_u = 1$. For F_u between 0 and 0.1, linear interpolation may be made between 1 and the value at $F_u = 0.1$. Thus, the new correlation is

$$E_R = 3.3F_u + 1, \quad \text{for } F_u < 0.1 \tag{9A}$$

$$E_R = 1.3F_u + 1.2, \quad \text{for } 0.1 \le F_u \le 1 \tag{9B}$$

$$E_R = 2.5, \quad \text{for } F_u > 1. \tag{9C}$$

6. Available correlations for occupied pools

By far the most widely used correlation is the following formula given by Carrier [8]:

$$E = \frac{(0.089 + 0.0782u)\Delta p}{i_{fg}} \tag{10}$$

where Δp is the vapor pressure difference between air saturated at pool surface temperature and the room air. This formula was based on tests done on an unoccupied pool along which air was blown. No tests were done without forced air flow. It has been widely used for calculating evaporation from pools without forced air flow by inputting $u = 0$ in the formula. The 1999 ASHRAE Handbook [9] recommends this equation for occupied public swimming pools with normal activity, partially wet deck, and some allowance for splashing. It may be mentioned that earlier books, such as the 1982 ASHRAE Handbook, recommended this formula for unoccupied indoor pools.

Shah [1] compared Eq. (10) with data for unoccupied pools from 11 sources. Almost all data were overpredicted, the average deviation for all data being +132% while the average deviations of individual data sets were up to +210%.

Smith et al. [4] conducted tests on occupied and unoccupied swimming pools and gave empirical formulas based on these data. Their formula for occupied pools may be written as

$$E = \frac{(0.068 + 0.063F_u)\Delta p}{i_{fg}}. \tag{11}$$

Biasin and Krumme [5] have given the following correlation of their own data, with F_u from 0.1 to 0.7:

$$E = 0.118 + 0.01995\,\Delta p F_u. \tag{12}$$

7. A new empirical correlation

Using the test data summarized in Table 1, it is possible to derive a variety of empirical equations through regression analysis. One such equation fitted by the present author is

$$E = 0.113 - 0.000079/F_u + 0.000059\,\Delta p. \tag{13}$$

This equation was based on data for $F_u > 0.1$. It is obviously inapplicable at $F_u = 0$, i.e. to unoccupied pools. For $F_u < 0.1$, the new phenomenological correlation, Eq. (9), may be used or linear interpolation may be made between the value for unoccupied pool and that at $F_u = 0.1$ from Eq. (13).

8. Comparison of data with correlations

The data discussed above and summarized in Table 1 were compared with the published correlations as well as with the two new correlations presented here.

For comparing the data with the new phenomenological correlation, Eq. (9), the evaporation at zero occupancy has to be calculated. It was decided to use the Shah correlation, Eq. (2), for this purpose as it has been shown to be the most accurate among the available calculation methods [1]. However, this could not be done for the data of Smith et al. [4] as they have not given sufficient details to make possible to calculate E_0 by the Shah correlation; instead they have listed E_R using their own correlation for unoccupied pools. As their unoccupied pool correlation was based on conditions similar to those during the occupied pool tests, it should have been satisfactory for this purpose.

For the data of Biasin and Krumme [5], the use of their own correlation for unoccupied pools to calculate E_0 instead of the Shah correlation was also considered but the results were much worse than with the use of the Shah correlation. Those results have not been reported here.

For some of the data of Biasin and Krumme [5], measured evaporation from occupied pools was found to be lower than the prediction of Eq. (2) for unoccupied pools. Such data were considered erroneous and were deleted. It may be mentioned that after a thorough examination, Shah [1] had concluded that the data of Biasin and Krumme [5] for unoccupied pools given in the same paper are erratic and generally low.

In the data of Doering [2], the actual number of pool occupants is not given. Instead, it is stated that the pool was full, half full, etc. The number of occupants was estimated considering full occupancy to be 4.5 m^2 per person.

Table 2
Results of comparison of test data with various correlations

Data of	Number of data points analyzed	Percent deviation from correlation of Mean Average				
		Smith et al. [4]	Biasin and Krumme [5]	Carrier [8]	Present phenomenological	Present empirical
Biasin and Krumme [5]	18	42.3 +41.3	34.0 +36.3	52.0 +57.9	26.7 +0.2	22.9 +16.2
Heimann and Rink [7]	4	35.8 +35.8	34.1 +34.1	13.4 −5.7	15.9 −15.9	16.0 −10.5
Doering [2]	5	21.8 +21.2	19.2 +2.8	16.4 +14.0	34.5 −28.4	6.1 −1.1
Smith et al. [4]	12	6.7 +3.2	29.4 +7.2	30.8 +27.8	25.7 +25.8	9.7 +2.3
All data	39	28.0 +26.4	30.7 +22.8	36.9 +36.4	26.3 +2.5	16.2 +7.0

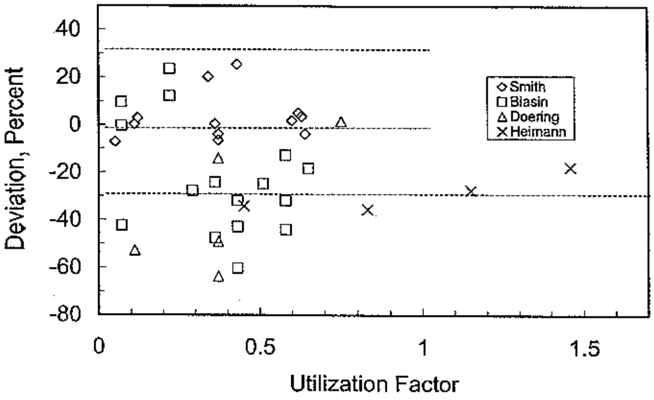

Fig. 1. Comparison of the correlation of Smith et al. [4] with data from all sources.

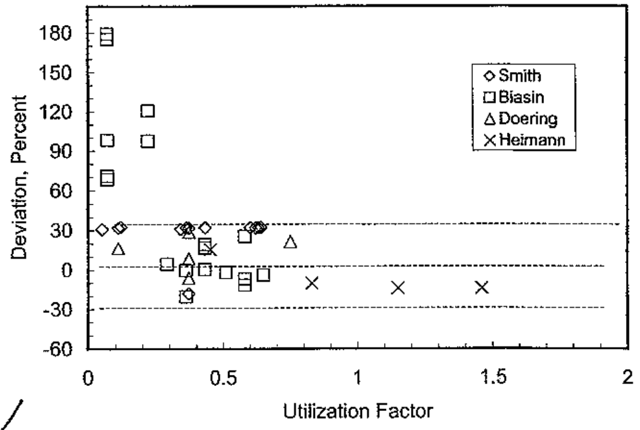

Fig. 2. Comparison of the Carrier correlation with data from all sources.

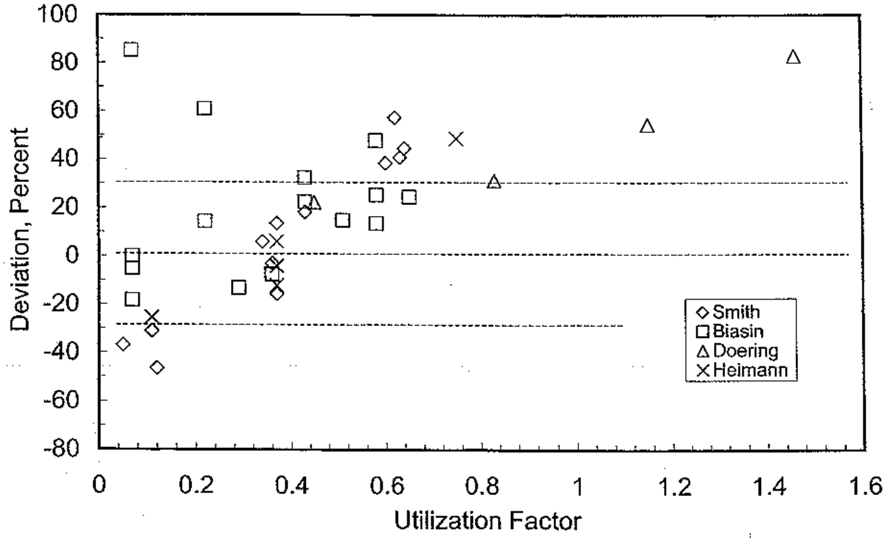

Fig. 3. Comparison of the Biasin and Krumme [5] correlation with data from all sources.

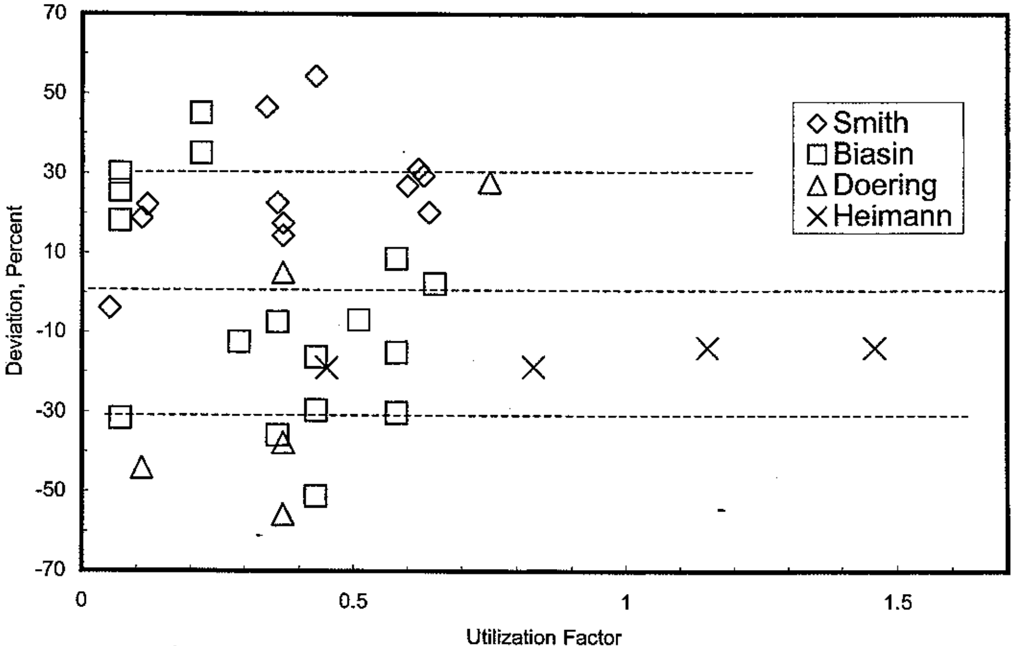

Fig. 4. Comparison of the new phenomenological correlation with all data.

The results of the comparison of the test data with correlations are given in Table 2 and Figs. 1–5. The deviation δ of a data point is defined as

$$\delta = \frac{\text{predicted}\, E - \text{measured}\, E}{\text{measured}\, E}. \qquad (14)$$

For the data sets, two types of deviations are defined as follows:

$$\text{average deviation} = \frac{\sum(\delta)}{\eta} \qquad (15)$$

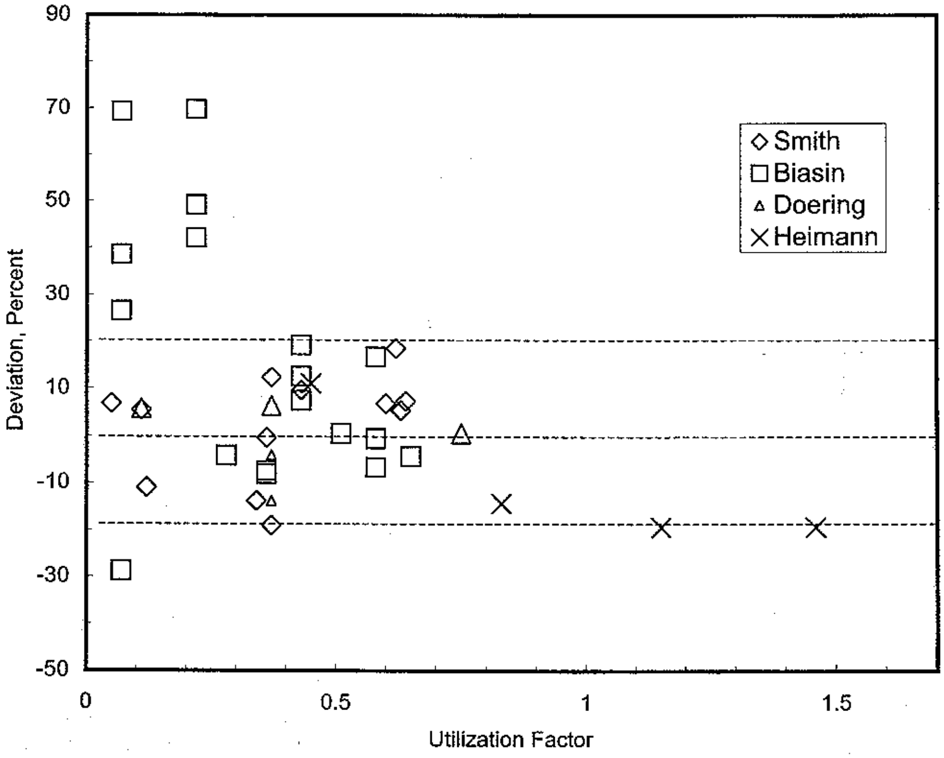

Fig. 5. Comparison of the new empirical correlation with all data.

$$\text{mean deviation} = \frac{\sum \text{abs.}(\delta)}{\eta} \quad (16)$$

where η is the number of data points.

The mean deviation of the new empirical correlation is 16.2% (it is near 10% if the data points of Biasin and Krumme [5] at very low F_u are ignored), that of the new phenomenological correlation is 26.3%, while the performance of the existing correlations is inferior.

9. Discussion

The new empirical correlation gives by far the best agreement with data, most of the data points being within ±20%. The new phenomenological correlation performs better than the published correlations. The correlation of Smith et al. [4] agrees well with their own data but performs poorly against all other data sets. The Carrier correlation was satisfactory at higher occupancies. The correlation of Biasin and Krumme [5] performed poorly against all data including their own.

As seen in Table 2, the new phenomenological correlation predicts on the average 26% higher than the data of Smith et al. [4] As noted earlier, these measurements had neglected the evaporation from the bodies of the occupants as well as the evaporation from wet deck and are therefore somewhat low. Thus this overprediction by this correlation is in line with expectation.

While the deviations of the phenomenological correlation from the available data are higher than those of the new empirical correlation, it is encouraging that this rational approach has shown reasonable agreement. Empirical correlations can be very inaccurate outside the range of data on which they are based. Hence, for air and water conditions outside the range of data in Table 1, the phenomenological correlation is likely to be more reliable.

It is seen that the larger deviations from the new correlations are at low occupancies. This may be due to physical phenomena. The activity level of individuals varies considerably. When there are many occupants, the mean effect averages out to normal activity level. But with only one or two persons in the pool, the differences in their activity have a large impact on the total evaporation. For example, a single occupant may be just standing in the water or swimming vigorously, creating waves, ripples and splashing on the deck. The evaporation in the latter case will clearly be much larger.

10. Summary and conclusion

1. Literature survey was done to identify available test data and correlations for evaporation from occupied indoor swimming pools. Analyzable data were found from four sources. Three correlations were found.
2. Two new correlations were developed, one considering the physical phenomena involved, and one purely empirical.
3. The new and existing correlations were compared with all data. The new empirical correlation gave by far the best agreement with a mean deviation of 16.2% and most data within ±20%. The next best was the phenomenological correlation with a mean deviation of 26.3%. The Carrier correlation gave a mean deviation of 36.9% but its performance at higher occupancies was satisfactory. The correlations of Biasin and Krumme [5] and Smith et al. [4] were found to be erratic.
4. The extent of agreement obtained with the new phenomenological correlation is encouraging. This rational approach is very desirable. It should be further tested and developed when more data become available. It is likely to be more reliable than the new empirical correlation outside the range of data analyzed here.

11. Design recommendations

1. In the range of data analyzed here, use the new empirical correlation, Eq. (13), at $F_u \geq 0.1$. Use the new phenomenological correlation, Eq. (9), at $F_u < 0.1$.
2. For conditions outside the range of data analyzed here, use the new phenomenological correlation, Eq. (9), at all values of F_u; E_0 to be calculated by the Shah correlation Eq. (2).

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