Analytical Formulas for Calculating Water Evaporation from Pools

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ABSTRACT

The calculation of water evaporation in pools (e.g., swimming pools) is needed for design and analysis. Numerous empirical equations for calculating water evaporation in undisturbed pools have been proposed and found inaccurate. Shah (1981, 1990, 2002) derived a formula using the analogy between heat and mass transfer that was shown to agree with almost all available data and is widely accepted. However, the complete derivation of this formula was unavailable until now, as only parts were presented in earlier papers. The complete derivation is given here. Results of comparisons with available test data for these and other published formulas for both disturbed and undisturbed pools are also given.

INTRODUCTION

The calculation of water evaporation in undisturbed pools into quiet air (i.e., air without forced flow) is required for many applications, including unoccupied indoor swimming pools, indoor water reservoirs, pools containing spent nuclear fuel, processing tanks, and water spills. Numerous empirical correlations have been presented, of which the best known is Carrier's correlation (1918). None of these has been found accurate when applied to data other than that on which they are based. The *2003 ASHRAE Handbook—HVAC Applications* (ASHRAE 2003) provides multiplication factors of values ranging from 0.5 to over 1.5 that can be applied to the Carrier correlation for pools in active use; no recommendations are made for unoccupied pools.

Shah (1981) presented a formula for calculating the evaporation of water in an undisturbed pool into quiet air that is derived from direct application of the analogy between heat and mass transfer. This formula underwent several modifications, presented in subsequent publications (Shah 1990, 1992, 2002), that resulted in a conveniently usable design equation. It was demonstrated that this formula shows good agreement with almost all available test data, while the empirical correlations show large discrepancies with all data except those on which they are based (Shah 2002).

Shah's formula is widely used in design calculations and energy analyses; however, its basis is not fully clear to most users, as only parts of the derivation of the final design equation are given in each of these publications. The primary purpose of this paper is to present the complete derivation in one place to make its bases comprehensible to all users.

Shah also presented an analytical formula and empirical correlation for evaporation in disturbed (i.e. occupied) pools in a 2003 publication (Shah 2003). As its derivation is fully described there, only the formula is given here.

Results of comparisons with test data for these and other published formulas were reported in earlier publications but are also given here so the reader can judge the reliability of these and other correlations without reference to earlier papers. Graphical representation of the results of data analyses are also provided.

FORMULA FOR UNDISTURBED WATER POOLS

Physical Phenomena

Consider first the case when room air dry bulb temperature is the same as the water surface temperature. Air in contact with the water surface becomes saturated with moisture and, thus, becomes lighter. The lighter air carrying moisture from the pool surface moves upwards, due to buoyancy, and the drier, heavier room air moves down to take its place.

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Thus, natural convection currents are set up. If the room air dry bulb temperature is lower than the water temperature, air in contact with water gains heat and becomes saturated at the water temperature and thus become lighter. The density difference is even greater than in the previous case, and the natural convection currents are stronger. If the room air dry bulb temperature is higher than the water surface temperature, air at the interface loses heat and becomes saturated at the water surface temperature. The density difference in this case is lower than in the first case and natural convection currents are weaker.

Derivation of the Formula

The formula is derived using the analogy between heat and mass transfer, considering the water surface to be a horizontal plate with the heated face upward.

The rate of evaporation is given by the following relation (Eckert and Drake 1972):

$$E_0 = h_M \rho_w (W_w - W_r) \tag{1}$$

The air density, ρ, is evaluated at the water surface temperature, as recommended by Kusuda (1965).

Heat transfer during turbulent natural convection to a heated plate facing upward is given by the following relation (McAdams 1954):

$$\mathrm{Nu} = 0.14(Gr_H \mathrm{Pr})^{1/3} \tag{2}$$

Using the analogy between heat and mass transfer, the corresponding mass transfer relation is

$$\mathrm{Sh} = 0.14(Gr_M \mathrm{Sc})^{1/3}. \tag{3}$$

Gr_M is defined as follows (Eckert and Drake 1972):

$$Gr_M = \frac{\gamma g (W_w - W_r) L^3 \rho^2}{\mu^2} \tag{4}$$

where

$$\gamma = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial W}\right) \tag{5}$$

Equation 5 may be approximately written as

$$\gamma = \frac{\rho_r - \rho_w}{\rho(W_w - W_r)}. \tag{6}$$

Combining Equations 4 and 6 gives the following:

$$Gr_M = \frac{g(\rho_r - \rho_w)L^3 \rho}{\mu^2} \tag{7}$$

Using Equation 7 and the definitions of Sh and Sc, Equation 3 becomes

$$\frac{h_M L}{D} = 0.14\left[\frac{(\rho_r - \rho_w)gL^3}{\mu D}\right]^{1/3}. \tag{8}$$

Combining Equations 1 and 8 gives the following:

$$E_0 = 0.14 g^{1/3} D^{2/3} \mu^{-1/3} \rho_w (\rho_r - \rho_w)^{1/3} (W_w - W_r) \tag{9}$$

The value of $D^{2/3}\mu^{-1/3}$ does not vary much over the temperature range of interest. Inserting a mean value, Equation 9 becomes:

$$E_0 = C \rho_w (\rho_r - \rho_w)^{1/3} (W_w - W_r) \tag{10}$$

where

C = 35 SI

It is noteworthy that Equations 9 and 10 have been derived from theory without any empirical adjustments.

Compared with experimental data, Equation 10 generally underpredicted when $\rho_r - \rho_w \le 0.02$ kg/m^3 on average by about 15% (Shah 2002). This is because, at such small density differences, the natural convection currents are weak. The effects of sideways air movement and stray air currents are significant and enhance the heat transfer beyond that due to natural convection. The values of C for low density difference, therefore, increase by 15%. The values of C become, in SI units,

$$C = 35 \text{ for } (\rho_r - \rho_w) > 0.02$$
$$C = 40 \text{ for } (\rho_r - \rho_w) \le 0.02$$

and, in I-P units (E in lb/ft^2·h, ρ in lb/ft^3),

$$C = 290 \text{ for } (\rho_r - \rho_w) > 0.00125$$
$$C = 333 \text{ for } (\rho_r - \rho_w) \le 0.00125$$

The values of ρ and W needed for Equation 10 are easily obtained from psychrometric charts and equations given in books such as *2005 ASHRAE Handbook—Fundamentals* (ASHRAE 2005).

ANALYTICAL FORMULA FOR OCCUPIED SWIMMING POOLS

Evaporation in occupied pools is known to be higher than in unoccupied pools. Shah attributed this increase to the increase in contact area between air and water due to waves on water surface, exposed wet bodies of occupants, wet deck, and splashing (2003). By analyzing these phenomena, he developed the following formula for evaporation rate E:

$$E/E_0 = 3.3F_u + 1 \quad \text{for } F_u < 0.1 \tag{11a}$$

$$E/E_0 = 1.3F_u + 1.2 \quad \text{for } 0.1 \le F_u < 1 \tag{11b}$$

$$E/E_0 = 2.5 \quad \text{for } F_u \ge 1 \tag{11c}$$

F_u is the pool utilization factor defined as the ratio of actual pool occupancy to the pool area per person at full occupancy. Thus,

$$F_u = \frac{(A_{pool}/N)}{A_{max}}. \tag{12}$$

A_{max} is the pool area per occupant at maximum occupancy. A figure of 4.5 m^2 was used per German standards (Biasin and Krumme 1974). A_{pool} is the area of the pool, and N is the number of pool occupants.

VARIOUS PUBLISHED CORRELATIONS

Numerous empirical correlations have been presented. The most widely known is Carrier's correlation (1918):

$$E = \frac{(0.089 + 0.0782u)(p_w - p_r)}{i_{fg}} \tag{13}$$

This formula was based on tests performed on a pool on which air was blown. No tests were performed without forced airflow. The formula has been widely used for calculating evaporation in unoccupied pools without forced airflow by inputting $u = 0$ in the formula. Many engineering books recommended such use. Earlier ASHRAE handbooks (for example *1982 ASHRAE Handbook—Applications* [ASHRAE 1982]) also recommended such use. The *2007 ASHRAE Handbook—HVAC Applications* (ASHRAE 2007) recommends this equation for occupied public swimming pools with normal activity and recommends correction factors (called activity factors) for other pools ranging from 0.5 for residential pools to 1.5 or greater for wave pools. These correction factors are for occupied pools; no guidance is provided for unoccupied pools.

Many empirical formulas for evaporation in undisturbed pools into quiet air have been published. Some of them are listed in Table 1. All of them are based only on the authors' own test data.

For occupied pools, Shah (2003) gave the following empirical formula by curve fitting to available test data for $F_u \geq 0.1$:

$$E = 0.113 - 0.000079/F_u + 0.000059(p_w - p_r) \tag{14a}$$

For $F_u < 0.1$, linear interpolation may be made between E_0 from Equation 10 and E at $F_u = 0.1$ from Equation 14a.

Equation 14a is in SI units, given in the nomenclature at the end of this paper. In I-P units, it becomes:

$$E = 0.023 - 0.0000162/F_u + 0.041(p_w - p_r) \tag{14b}$$

E is in lb/ft^2·h, and p is in inches of mercury. Note that in calculating F_u with Equation 12, A_{max} is 48.4 ft^2 and A_{pool} is in square feet.

Biasin and Krumme (1974) and Smith et al. (1999) have given empirical correlations based on their own measurements of evaporation from occupied swimming pools.

COMPARISON OF DATA WITH CORRELATIONS

Shah (2002, 2003) collected all available data for undisturbed pools, as well as from occupied swimming pools, and compared them to his own formulas and the other formulas mentioned earlier. The range of data analyzed for undisturbed pools and occupied swimming pools is given in Tables 2 and 4, respectively. The results of the comparison are summarized in Tables 3 and 5, respectively. Deviation δ of a data point is defined as:

$$\delta = (\text{prediction} - \text{measurement})/\text{measurement}$$

Mean absolute deviations are based on the absolute values of δ; average deviations are based on the actual values of δ.

DISCUSSION OF RESULTS OF COMPARISON

Undisturbed Water Pools

As seen in Table 3, the Shah formula gives best overall agreement with data with a mean deviation of 20.6%. The next best agreement is with the Boelter et al. (1946) equation (Equation 18), which has a mean deviation of 25.8%. The mean deviations of other correlations range from high to very high. The data include sizes from small laboratory vessels to large public swimming pools (0.073 to 425 m^2 surface area) and a wide range of water and air temperatures and humidities. All but one data set are in good agreement with the Shah formula. This gives confidence in its reliability.

The widely used Carrier correlation has a mean absolute deviation of 136% and an average deviation of +132%. Thus, almost all data are overpredicted. The mean absolute deviations of data sets vary from 28% to 210%. Therefore, it cannot be corrected by a simple multiplying factor as was attempted by Smith et al. (1993). The failure of this correlation and others of this type listed in Table 1 shows that factors other than vapor pressure difference are involved in determining evaporation rates. It should be emphasized that the 2003 ASHRAE Handbook (ASHRAE 2003) does not say that this formula can be used for evaporation in unoccupied swimming pools.

Figure 1 shows the comparison of the formulas of Shah and Carrier with some data from a small vessel. The Shah formula shows good agreement with almost all data; whereas, on the other hand, deviations of the Carrier formula are large. It is seen that the deviations of the Carrier formula increase with decreasing value of the air density difference $(\rho_r - \rho_w)$. This indicates this factor is needed for correlating evaporation; satisfactory predictions are not possible using the vapor pressure difference alone, as in the Carrier formula and most of the formulas listed in Table 1.

Figure 2 shows the comparison of the Carrier and Shah formulas with data from unoccupied large swimming pools. The results are similar to those for the small vessel shown in Figure 1.

There were a few data points in which $\rho_r - \rho_w$ was negative. This situation is similar to a heated plate facing downward and, hence, Equation 10 is not applicable. The analogy could be used to develop a similar formula for this case. However, this effort was not considered worthwhile, as there were very few data points for this situation. Instead, Equation 10 was applied using the absolute value of the density differ-

Table 1. Various Empirical Correlations for Undisturbed Water Pools

Author	Correlation	Equation Number
Smith et al. (1993)	$E = \dfrac{0.76(0.089+0.0782u)(p_w-p_r)}{i_{fg}}$	15
Biasin and Krumme (1974)	$E = -0.059+0.000079(p_w-p_r)$	16
Rohwer (1931)	$E = 0.08(t_w-t_r+3)^{2/3}(p_w-p_r)$	17
	for $\Delta x < 0.008$, $E = 5.71\Delta x$	18a
Boelter et al. (1946)	for $0.008 < \Delta x \le 0.016$, $E = 4.88(-0.024+4.05795\Delta x)$	18b
	for $\Delta x > 0.016$, $E = 38.2(\Delta x)^{1.25}$	18c
Tang et al. (1993)	$E = 35(\Delta x)^{1.237}$	19
Boelter et al. (1946)	$E = 0.0000162(p_w-p_r)^{1.22}$	20
Himus and Hinchley (1924)	$E = 0.0000258(p_w-p_r)^{1.2}$	21
Leven (1969)	$E = 0.00000945(p_w-p_r)^{1.3}$	22
Box (1876)	$E = 0.0000778(p_w-p_r)$	23

Table 2. Summary of Test Data for Evaporation from Undisturbed Water Pools

Researcher	Pool Area, m^2	Water Temperature, °C	Air Temperature, °C	Air Humidity, %	p_w-p_r, Pa	$\rho_r-\rho_w$, kg/m^3	Evaporation Rate, $kg/m^2{\cdot}h$	Notes
Bohlen (1972)	32	25.0	27.0	60	1029	0.0043	0.052	1
Boelter et al. (1946)	0.073	24.0 94.2	18.7 24.7	64 98	1272 80,156	0.022 1.0025	0.082 21.07	2
Rohwer (1931)	0.837	7.1 16.5	6.1 17.2	69 78	247 638	0.0049 0.0080	0.010 0.040	2
Sharpley and Boelter (1938)	0.073	13.9 33.4	21.7	53	210 3786	−0.0049 0.088	0.018 0.402	2
Biasin and Krumme (1974)	62.2	24.3 30.1	24.3 34.6	40 68	1010 2128	0.0007 0.030	0.030 0.154	1
Sprenger (c. 1968)	200	28.5	31.0	54 55	1422 1467	0.0070 0.0076	0.070 0.235	1
Tang et al. (1997)	1.13	25.0	20.0	50	2001	0.0433	0.168	2
Reeker (1978)	Note 3	23.0	25.5	71	493	−0.004	0.035	1
Smith et al. (1993)	404	28.3	21.7 27.8	51 73	1127 1990	0.0150 0.0554	0.090 0.246	1
Doering (1979)	425	25.0	27.5	28	2142	0.0153	0.175	1
All Sources	0.073 425.0	7.1 94.2	6.1 34.6	28 98	210 80,156	−0.004 +1.002	0.010 21.073	

Notes: (1) Field tests (2) laboratory tests (3) private pool (size not given)

ence. The agreement with data was satisfactory, but this does not establish a general applicability of this methodology, and it is therefore not recommended.

Occupied Pools

As seen in Table 5, Shah's empirical correlation (Equation 14a) gives by far the best agreement with data, as most of the data points are within ±20%. Shah's analytical correlation (Equation 11) performs better than other published correlations considering all data. However for $F_u > 0.22$, the Carrier correlation (recommended by *2007 ASHRAE Handbook—HVAC Applications* [2007]) performs somewhat better than the analytical correlation. The correlation of Smith et al. (1999) agrees well with their own data but performs poorly

Table 3. Results of Comparison of Data for Undisturbed Water Pools from All Sources with All Formulas

Data of	Number of Data Points Analyzed	Percent Deviation from Correlation of Mean ~~Absolute~~ Average										
		Biasin and Krumme (1974)	Box (1946)	Leven (1969)	Rohwer (1931)	Himus and Hinchley (1924)	Boelter et al. (1946), Equation 20	Boelter et al. (1946), Equation 18	Tang et al. (1993)	Carrier (1918)	Smith et al. (1993)	Shah Equation 10
Rohwer (1931)	40	310.3	74.6	40.6	21.2	86.2	44.4	35.0	52.3	210.5	137.4	20.4
		–310.3	69.8	19.9	6.2	81.9	28.4	–5.3	42.4	210.4	135.9	–3.1
Bohlen (1972)	1	57.1	54.0	49.9	NA	104.5	47.4	16.7	60.5	181.5	111.1	3.6
		–57.1	54.1	49.9		104.5	47.4	–16.7	60.5	181.5	111.1	–3.6
Smith et al. (1993)	5	56.5	20.1	9.0	30.8	17.7	14.3	27.6	10.1	45.3	9.5	14.6
		–56.5	–20.1	–9.0	5.4	17.7	–14.3	–27.6	–10.1	45.3	9.5	–14.6
Boelter et al. (1946)	24	49.6	44.6	27.7	188.9	31.9	7.5	7.3	9.9	28.2	30.6	12.0
		–49.6	–4.3	27.7	188.9	31.4	0.1	–3.0	–4.3	8.0	–17.9	10.2
Sharpley and Boelter (1938)	28	59.2	39.8	35.1	65.9	72.7	31.3	10.1	38.6	121.4	68.4	20.1
		–59.2	21.1	31.0	55.6	71.9	24.8	0.9	35.3	121.4	68.2	12.2
Biasin and Krumme (1974)	1 (Note 1)	18.7	63.0	76.5	NA	132.4	68.7	34.8	82.1	198.0	126.5	22.0
		–18.7	63.0	76.5		132.4	68.7	34.8	82.1	198.0	126.5	22.0
	9 (Note 2)	16.0	63.0	89.7	40.2	143.8	77.9	67.8	91.0	198.0	126.5	44.7
		–1.0	63.0	89.7	19.6	143.8	77.9	67.8	91.0	198.0	126.5	34.8
Tang et al. (1993)	1	41.0	7.3	10.1	58.6	40.5	2.7	0.0	9.8	69.4	28.7	7.7
		–41.0	–7.3	10.1	58.6	40.5	2.7	0.0	9.8	69.4	28.7	7.7
Reeker (1978)	1	156.9	8.6	15.3	NA	24.4	11.6	39.4	1.2	98.6	48.8	11.3
		–156.9	8.6	–15.3		24.4	–11.6	–39.4	–1.2	98.5	48.8	–11.3
Doering (1979)	1	37.0	4.8	15.5	NA	40.5	2.7	0.0	9.8	69.4	27.0	10.1
		–37.0	–4.8	–15.5		40.5	2.7	0.0	9.8	69.4	27.0	–10.1
All Data	111	137.2	52.5	39.2	74.4	73.2	34.1	25.8	40.7	136.2	86.8	20.6
		–135.9	32.8	30.4	60.6	71.4	24.3	3.9	32.8	132.1	76.4	7.5

Notes: (1) Pool area 200^2; (2) pool area 2.2 m^2

Table 4. Range of Published Data on Measurement of Evaporation from Active Swimming Pools

Researcher	Pool Area, m^2	Air Temperatures, C	Air RH, %	Water Temperature, C	$p_w - p_r$, Pa	$\rho_r - \rho_w$, kg/m^3	F_u	Maximum Number of Persons
Doering	425	27.5 29.0	33 41	25.0	1527 1921	0.0024 0.0123	0.11 0.75	71
Biasin and Krumme	64	26.0 31.7	46 72	26.0 30.0	1067 2069	0.0013 0.218	0.07 0.65	8
Heimann and Rink	200	31.0	54 55	28.5	1422	0.007	0.45 1.46	65
Smith et al. (1999)	1209	29.4	50	26.7 27.8	1454 1731	0.0069 0.0147	0.05 0.64	180
All Data	64 1209	27.0 31.7	33 72	25.0 30.0	1067 2069	0.0013 0.218	0.05 1.46	8 180

Table 5. Results of Comparison of Test Data for Occupied Swimming Pools with Various Correlations from Shah (2003)

Data of	Number of Data Points Analyzed	Percent Deviation from Correlation of Mean ~~Absolute~~ Average				
		Smith	Biasin and Krumme	Carrier (ASHRAE Handbook)	Shah Analytical	Shah Empirical
Biasin and Krumme	18	42.3 +41.3	34.0 +36.3	52.0 +57.9	26.7 +0.2	22.9 +16.2
Heimann and Rink	4	35.8 +35.8	34.1 +34.1	13.4 −5.7	15.9 −15.9	16.0 −10.5
Doering	5	21.8 +21.2	19.2 +2.8	16.4 +14.0	34.5 −28.4	6.1 −1.1
Smith et al. (1999)	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

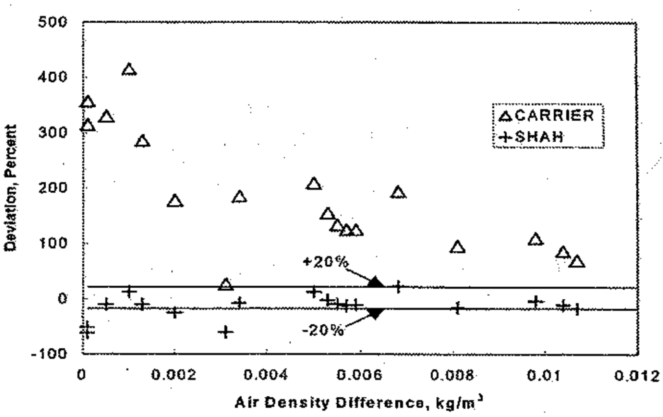

Figure 1 *Comparison of the Shah and Carrier formulas with the Rohwer data for evaporation in a vessel area of 0.84 m^2.*

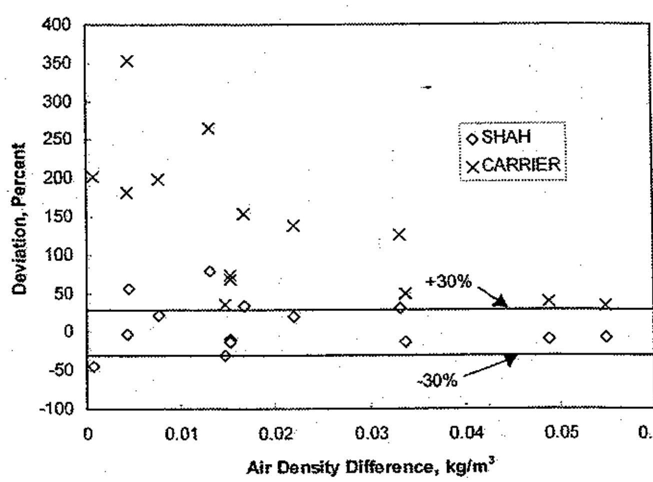

Figure 2 *Data for unoccupied swimming pools (area of 32 to 425 m^2) compared with the Shah and Carrier formulas.*

against other data sets. The correlation of Biasin and Krumme (1974) performed poorly against all data, including their own.

As seen in Table 5, the analytical correlation predicts on the average 26% higher than the data of Smith et al. (1999). In this study, evaporation was determined from the heat added to pool water and, hence, did not include the evaporation from the bodies of the occupants or the evaporation from the wet deck and is, therefore, somewhat low. Thus, the overproduction by this correlation is in line with expectations.

While the deviations of the analytical correlation from the available data are higher than those of the new empirical correlation, it is encouraging that this rational approach shows 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 4, the analytical correlation is likely to be more reliable.

Figures 3, 4, and 5 show the comparison of data with the method recommended by ASHRAE Handbook, Shah's empirical formula (Equation 14a), and Shah's analytical formula (Equation 11). Deviations are higher at lower occupancies for all three methods. The likely explanation is that the statistical variation between activity levels of a few people is likely to be much more than that of many people. Thus, a single occupant may swim vigorously or sit at the edge of pool. The activity level for many occupants is likely to average out.

Effect of Air Density Difference

As stated earlier, there were a few data points in which $p_r - p_w$ was negative. This situation is similar to a heated plate facing downward, while Equation 10 was derived on the basis of similarity with a heated plate facing upwards. The analogy could be used to develop a similar formula for this case. However, this effort was not considered worthwhile, as there were very few data points for this situation. Instead, Equation 10 was applied using the absolute value of the density difference. The agreement with data was satisfactory; however, this does not establish its general applicability of this methodology and it is, therefore, not recommended. The author's formulas are recommended only when the density difference is positive. The lowest positive air density difference satisfactorily correlated was 0.0043 kg/m^3. This is the minimum density difference for which the author's formulas are recommended.

Effect of Air Velocity

The occupied pool data analyzed here were obtained through tests on public swimming pools with typical air-conditioning systems. The data for unoccupied pools included four public swimming pools. While the actual air velocity at the pool surface has not been reported, the 2007 ASHRAE Handbook (2007) states that it should not exceed 9 m/min. Downward discharge grilles are usually selected to give 15 m/min. velocity at floor level. While it is possible that

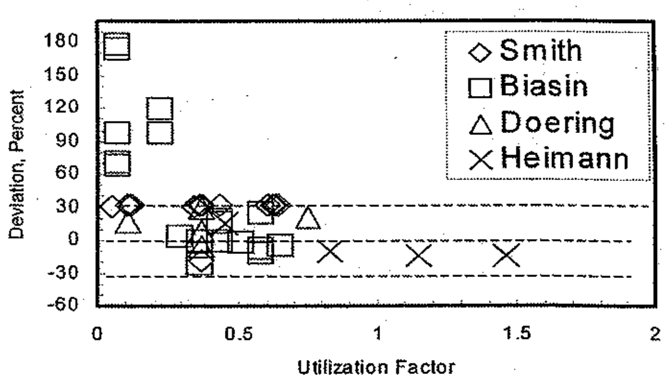

Figure 3 *Comparison of data for occupied public swimming pools with the method recommended by ASHRAE Handbook (i.e., the Carrier formula [Equation 13]) (Shah 2003).*

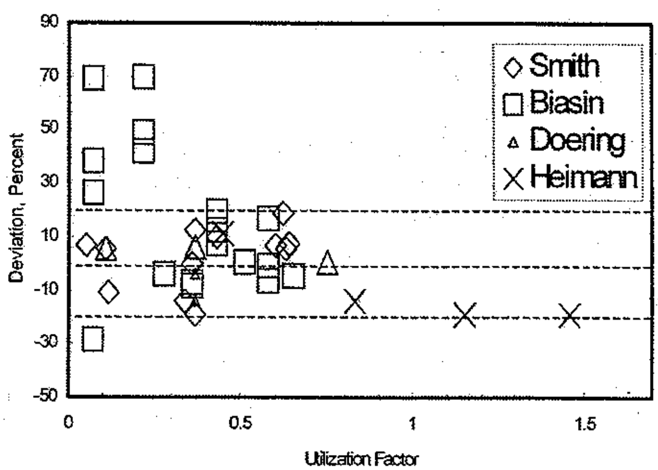

Figure 4 *Comparison of data from several sources for occupied pools with Shah's empirical formula (Equation 14) (Shah 2003).*

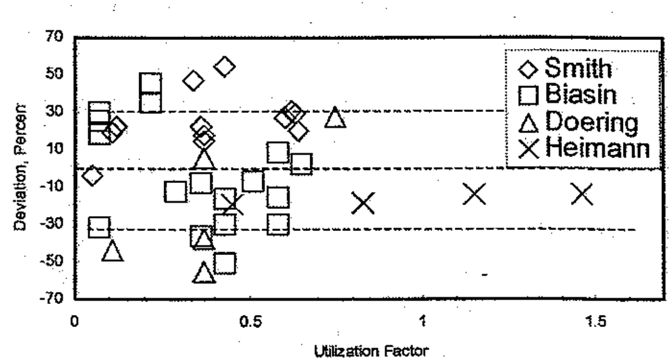

Figure 5 *Comparison of data for occupied pools with Shah's analytical correlation (Equation 11) (Shah 2003).*

the actual air velocity during tests may have been higher, the author's formulas are recommended only for velocities (horizontal or vertical) of 9 m/min. or less.

Himus and Hinchley (1924) performed tests in quiet air and with air flowing parallel to the water surface and gave formulas for both situations. Their formula for forced airflow is similar to the Carrier formula. Extrapolation of their forced-flow formula to zero velocity resulted in up to 300% overprediction of their quiet air data. They concluded that formulas for forced airflow cannot be extrapolated to quiet air. Lurie and Michailoff (1936) reached the same conclusion. Shah does not favor use of such correction factors. Complex treatments of mixed convection situations have been published, but the author has not evaluated them.

Shah recommends his formulas for disturbed and undisturbed water pools be used only when velocity at water surface does not exceed 9 m/min. These formulas are not recommended for systems with high horizontal or vertical velocities, such as in push-pull systems or jets blowing over the water surface.

SUMMARY AND CONCLUSION

1. The complete derivation of the author's analytical formula for evaporation in undisturbed water pools is given. Previous publications gave only parts of the derivation and, hence, its theoretical bases were unclear to users. Engineers will now be able to use the derivation with more understanding and confidence.
2. The author's analytical and empirical formulas for occupied swimming pools, in addition to other published correlations, are also given.
3. The results of comparison of the author's and other published formulas with available test data for undisturbed pools and occupied swimming pools are given and discussed.
4. The results of comparisons with test data show that, for undisturbed pools, the author's analytical formula is the most reliable among the numerous published correlations. For occupied swimming pools, the methodology of the 2007 ASHRAE Handbook (2007) works fairly well, but the author's empirical and analytical formulas perform better and may, therefore, be preferable.
5. The author's formulas are recommended only for air velocities at water surface not exceeding 9 m/min. and air density difference $\rho_r - \rho_w$ not less than +0.0043 kg/m^3.

NOMENCLATURE

The SI units given below apply for all equations in this paper except where specifically noted otherwise.

D = coefficient of molecular diffusivity, m^2/h

E = rate of evaporation from occupied pools, kg/m^2·h

E_0 = rate of evaporation from un-occupied pools, kg/m^2·h

F_u = pool utilization factor, defined by Equation 12

Gr_H = Grashof number for heat transfer, dimensionless

Gr_M = Grashof number for mass transfer, dimensionless

g = acceleration due to gravity, m/h^2

i_{fg} = latent heat of vaporization of water, kJ/kg

h_M = mass transfer coefficient, m/h

L = characteristic length of water pool, m

Nu = Nusselt number, dimensionless

Pr = Prandtl number, dimensionless

p = partial pressure of water vapor in air, Pa

Sc = Schmidt number = $\mu/\rho D$, dimensionless

Sh = Sherwood number, = $h_M L/D$, dimensionless

u = air velocity, m/s

W = specific humidity of air, kg of moisture/kg of air

x = concentration of water in air, kg/m^3

μ = dynamic viscosity of air, kg/m·h

ρ = density of air, mass of dry air per unit volume of moist air, kg/m^3 (This is the density in psychrometric charts and tables.)

$\Delta\rho$ = $\rho_r - \rho_w$

Δx = $x_w - x_r$

Subscripts

w = saturated at water surface temperature

r = at room temperature and humidity

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