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Evaluation of Available Correlations for Rate of Evaporation from Undisturbed Water Pools to Quiet Air

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Calculation of evaporation from undisturbed water surfaces to quiet air is required for many applications, including unoccupied indoor swimming pools, pools containing spent nuclear fuel, indoor water reservoirs, process tanks, and contaminated water spills. Many correlations have been proposed for such calculations but none have had sufficient verification. Data from 11 sources that included pool sizes from 0.07 to 425 m^2, water temperatures from 7 to 94°C, air temperatures from 6 to 35°C, and humidity from 28 to 95% were available in the literature, and 11 correlations had been developed. The available correlations were compared to the data to test their validity over a wide range of conditions. The correlation of Shah (1992), which is derived from the analogy between heat and mass transfer, gave the best agreement with a mean deviation of 18.2%. The second best was the correlation of Boelter et al. (1946), with a mean deviation of 26.2%. All other correlations had unacceptably high deviations. The Shah correlation is recommended for design calculations, with the Boelter correlation as an alternative.

INTRODUCTION

Calculating evaporation from water pools into quiet air (i.e., air without forced flow) is required in many applications, such as indoor swimming pools, indoor water reservoirs, pools containing spent nuclear fuel, process tanks, and water spills. Accurate estimation of the rate of evaporation is important for correctly sizing the air-conditioning equipment. An underestimate will result in selecting an air-conditioning unit that is unable to keep humidity low enough to keep occupants comfortable and the building free of fungus and rot. An overestimate will result in selection of an oversized unit with high cost, high energy consumption, and operating problems due to frequent cycling. For water reservoirs, the rate of evaporation is required to estimate the amount of water loss. For a spill of contaminated water, it may be desirable to know the time needed for drying.

It is well known that rate of evaporation from disturbed water surfaces is higher than that from undisturbed surfaces; for example, Doering (1979) compared occupied and unoccupied swimming pools. Although calculations of evaporation rates are needed for both cases, this work deals only with evaporation from undisturbed water.

Numerous empirical correlations for calculation of evaporation in quiet air have been proposed. None of them have been verified with more than a few data sets and thus cannot be used with confidence for designs. The present author developed a simple formula using the analogy between heat and mass transfer (Shah 1981, 1990, 1992). It was shown to agree with a few data sets, but further verification was desirable. Yilmaz and Aybar (1999) compared the predictions of several correlations with one another but did not compare them to actual data. A comparison of a predictive technique with data from several sources has not been done.

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In this paper, the available correlations are tested against a wide range of data to determine those best for use in designs.

AVAILABLE CORRELATIONS

The Shah correlation (1981, 1990, 1992) was derived using the analogy between heat and mass transfer, considering the pool surface to be a plate with heated surface facing upward:

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

where $C = 35$ in SI units.

For $(\rho_r - \rho_w) < 0$, Shah (1992) analyzed a few data points by inserting the absolute value of $(\rho_r - \rho_w)$ in Equation (1) and obtained satisfactory agreement.

During the present data analyses, it was noticed that Equation (1) generally underpredicts evaporation when $(\rho_r - \rho_w) \le 0.02$ kg/m^3, on the average by about 15%. This error is attributed to enhancement of natural convection by sideways air movement and stray air currents. The values of C for low density differences are therefore increased by 15%. The values of C thus 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 (1) are obtained from psychrometric charts and equations given in books such as the 1997 *ASHRAE Handbook—Fundamentals*.

Other Correlations

Other published correlations are listed in Table 1. All these correlations are in SI units except for Rohwer's (1931), which gives E in inches of water per 24 h, t (temperature of room air) in °F, and p in inches of mercury.

Among these correlations, the most widely known is that of Carrier (1918). This formula was based on tests done on a pool along which air was blown. No tests were done without forced air flow, and the correlation has been widely used for calculating evaporation from unoccupied pools without forced air flow by setting u to 0 in the formula. Many engineering books and earlier ASHRAE Handbooks (e.g., 1982 *ASHRAE Handbook—Applications*) recommended such use. The 1999 *ASHRAE Handbook—HVAC Applications* recommends this equation for occupied public swimming pools. A number of researchers (e.g., Himus and Hinchley 1924; Lurie and Michailoff 1936; and Rohwer 1931) have concluded, based on their own experimental works, that the formulas based on forced air flow data cannot be applied to situations without forced air flow.

MEASUREMENTS OF EVAPORATION

Efforts were made to obtain as much data for measured evaporation rates as possible; these data are summarized in Table 2. All these data are for unoccupied, undisturbed pools; they cover a wide range of parameters and include field measurements as well as laboratory measurements.

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Table 1. Various Empirical Correlations

Author	Correlation	Eqn. No.
Carrier (1918)	$E = \dfrac{(0.089 + 0.0782u)(p_w - p_r)}{i_{fg}}$	(2)
Smith et al. (1993)	$E = \dfrac{0.76(0.089 + 0.0782u)(p_w - p_r)}{i_{fg}}$	(3)
Biasin and Krumme (1974)	$E = -0.059 + 0.000079(p_w - p_r)$	(4)
Rohwer (1931)	$E = 0.08(t_w - t_r + 3)^{2/3}(p_w - p_r)$	(5)
Boelter et al. (1946)	For $\Delta x < 0.008$, $E = 5.71\Delta x$	(6a)
	For $0.008 < \Delta x \le 0.016$, $E = 4.88\ (-0.024 + 4.05795\Delta x)$	(6b)
	For $\Delta x > 0.016$, $E = 38.2\ (\Delta x)^{1.25}$	(6c)
Tang et al. (1993)	$E = 35(\Delta x)^{1.237}$	(7)
Boelter et al. (1946)	$E = 0.0000162(p_w - p_r)^{1.22}$	(8)
Himus and Hinchley (1924)	$E = 0.0000258(p_w - p_r)^{1.2}$	(9)
Leven (c. 1969)	$E = 0.0000945(p_w - p_r)^{1.3}$	(10)
Box (1876)	$E = 0.0000778(p_w - p_r)$	(11)

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

Researcher	Pool Area, m^2	Water Temp., °C	Air Temp., °C	Air Humidity, %	$p_w - p_r$, Pascal	$\rho_r - \rho_w$, 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
Kiesling (1989)	36	26.2	26.7	40	1240	0.0106	0.093	1
	409	32.2	27.8	60	2539	0.0491	0.174	
Boelter et al. (1946)	0.073	24.0	18.7	64	1272	0.022	0.082	2
		94.2	24.7	98	80156	1.0025	21.07	
Rohwer (1931)	0.837	7.1	6.1	69	247	0.0049	0.010	2
		16.5	17.2	78	638	0.0080	0.040	
Sharpley and Boelter (1938)	0.073	13.9	21.7	53	210	−0.0049	0.018	2
		33.4			3786	0.088	0.402	
Biasin and Krumme (1974)	62.2	24.3	24.3	40	1010	0.0007	0.030	1
		30.1	34.6	68	2128	0.030	0.154	
Sprenger (c. 1968)	200	28.5	31.0	54	1422	0.0070	0.070	1
				55	1467	0.0076	0.235	
Tang et al. (1993)	1.13	25.0	20.0	50	2001	0.0433	0.168	2
Reeker (1978)	3	23.0	25.5	71	493	−0.004	0.035	1
Smith et al. (1993)	404	28.3	21.7	51	1127	0.0150	0.090	1
			27.8	73	1990	0.0554	0.246	
Doering (1979)	425	25.0	27.5	28	2142	0.0153	0.175	1
All Sources	0.073	7.1	6.1	28	210	−0.004	0.010	
	425.0	94.2	34.6	98	80156	+1.002	21.073	

Notes: [1] Field tests [2] Laboratory tests [3] Private pool, size not given

In the laboratory tests, evaporation was determined by measuring the changes in water level using appropriate equipment. In the field measurements, evaporation was taken to be the amount of condensate collected from the cooling coil of the air-conditioning unit. The exception are the measurements of Smith et al. (1993), which were done on a large public swimming pool where the evaporation rate was obtained by measurements of water level.

COMPARISON OF DATA WITH CORRELATIONS

The test data listed in Table 2 were compared with the correlations that have been recommended for evaporation into quiet air from undisturbed water surfaces listed earlier. Table 3 presents the results of comparison of all data with all such correlations. The deviation δ of a data point is defined as

$$\delta = \frac{\text{prediction} - \text{measurement}}{\text{measurement}}$$

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

DISCUSSION OF RESULTS

It is seen from Table 3 that the Shah formula, Equation (1), gives best overall agreement with data with a mean deviation of 20.6%. The next best is the Boelter et al. (1946), Equation (6), which has a mean deviation of 25.8%. The mean deviations of other correlations are seen to range from high to very high.

The widely used correlation by Carrier has a mean deviation of 136%, and an average deviation of +132%. Thus, almost all data are overpredicted. The results of the Carrier formula are as expected: the 1999 *ASHRAE Handbook—HVAC Applications* recommends it for occupied public pools with normal activity, partially wet deck, and some allowance for splashing, whereas the data analyzed here are for unoccupied pools. The same reference indicates that evaporation from an occupied public pool is twice that from a private pool. The formula of Smith et al. (1993) gives evaporation rates of 76% of those from the Carrier formula, and also overpredicts most of the data, with an average deviation of +76.4%.

The Shah formula has a mean deviation of 44.7% from the data of Biasin and Krumme (1974), the data being mostly overpredicted. The Biasin-Krumme correlation, which is based on their own data, underpredicts all data except their own as seen in Table 3. The data are lower than all others and it appears likely that the measurements are inaccurate. The Shah correlation has a mean deviation of 33.9% from the data of Kiesling (1989). These data are lower than predicted by most of the other formulas; the deviation of the Boelter et al. (1946) Equation (6) is 50.4%. These are field data and could be somewhat inaccurate.

Although the deviations from the two sets of field data discussed above (Kiesling 1989; Biasin and Krumme 1974) are somewhat high, the Shah corrrelation shows good agreement with the other nine data sets. Most of the other correlations show good agreement only with the data to which they were fitted, with large deviations from the other data.

It is concluded that the Shah correlation is the most reliable among the available ones. The only other correlation which can be considered to be reliable is the Boelter et al. (1946) Equation (6), but it is significantly less accurate than the Shah correlation.

The Shah formula involves the density difference $\Delta\rho$. Table 4 shows the deviations of the Shah correlation and the Boelter et al. (1946) Equation (6) in various ranges of $\Delta\rho$. Other correlations are not included because, as shown in Table 3, they are very inaccurate. The mean devia-

Table 3. Results of Comparison of Data from All Sources with All Formulas

Number of Data	Percent Deviation From Correlation of Mean Average	
	Boelter	Boelter

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Table 3. Results of Comparison of Data from All Sources with All Formulas

Data of	Number of Data Points Analyzed	Percent Deviation From Correlation of Mean Average										
		Biasin and Krumme	Box	Leven	Rohwer	Himus and Hinchley	Boelter et al. Eq. (8)	Boelter et al. Eq. (6)	Tang et al.	Carrier	Smith et al.	Shah
Rohwer	40	310.3 −310.3	74.6 69.8	40.6 19.9	21.2 6.2	86.2 81.9	44.4 28.4	35.0 −5.3	52.3 42.4	210.5 210.4	137.4 135.9	20.4 −3.1
Bohlen	1	57.1 −57.1	54.0 54.1	49.9 49.9	NA	104.5 104.5	47.4 47.4	16.7 −16.7	60.5 60.5	181.5 181.5	111.1 111.1	3.6 −3.6
Smith et al.	5	56.5 −56.5	20.1 −20.1	9.0 −9.0	30.8 5.4	17.7 17.7	14.3 −14.3	27.6 −27.6	10.1 −10.1	45.3 45.3	9.5 9.5	14.6 −14.6
Kiesling	7	25.0 −22.2	26.7 24.1	48.2 48.1	61.6 6.0	88.7 88.7	39.3 37.9	50.4 34.8	46.2 46.2	126.2 126.2	71.9 71.9	33.9 25.2
Boelter et al.	24	49.6 −49.6	44.6 −4.3	27.7 27.7	188.9 188.9	31.9 31.4	7.5 0.1	7.3 −3.0	9.9 −4.3	28.2 8.0	30.6 −17.9	12.0 10.2
Sharpley and Boelter	28	59.2 −59.2	39.8 21.1	35.1 31.0	65.9 55.6	72.7 71.9	31.3 24.8	10.1 0.9	38.6 35.3	121.4 121.4	68.4 68.2	20.1 12.2
Sprenger	1	18.7 −18.7	63.0 63.0	76.5 76.5	NA	132.4 132.4	68.7 68.7	34.8 34.8	82.1 82.1	198.0 198.0	126.5 126.5	22.0 22.0
Biasin and Krumme	9	16.0 −1.0	63.0 63.0	89.7 89.7	40.2 19.6	143.8 143.8	77.9 77.9	67.8 67.8	91.0 91.0	198.0 198.0	126.5 126.5	44.7 34.8
Tang et al.	1	41.0 −41.0	7.3 −7.3	10.1 10.1	58.6 58.6	40.5 40.5	2.7 2.7	0.0 0.0	9.8 9.8	69.4 69.4	28.7 28.7	7.7 7.7
Reeker	1	156.9 −156.9	8.6 8.6	15.3 −15.3	NA	24.4 24.4	11.6 −11.6	39.4 −39.4	1.2 −1.2	98.6 98.5	48.8 48.8	11.3 −11.3
Doering	1	37.0 −37.0	4.8 −4.8	15.5 −15.5	NA	46.4 46.4	7.1 7.1	9.9 9.9	16.6 16.6	74.0 74.0	32.3 32.3	10.1 −10.1
All Data	118	137.2 −135.9	52.5 32.8	39.2 30.4	74.4 60.6	73.2 71.4	34.1 24.3	25.8 3.9	40.7 32.8	136.2 132.1	86.8 76.4	20.6 7.5

Table 4. Deviations of the Shah Correlation and Boelter et al. (1946) Equation (6) in Various Ranges of Density Difference Between Room Air and Air Saturated at Pool Water Temperature

Density Difference $(\rho_r - \rho_w)$, kg/m^3	No. of Data Sets	No. of Data Points	Mean Deviation, %			
			Equal Weight to Each Data Set		Equal Weight to Each Data Point	
			Shah	Boelter	Shah	Boelter
>0.02	7	52	17.7	20.2	14.3	11.7
0 to 0.02	8	60	24.9	35.5	26.7	37.6
<0	3	6	12.4	23.0	14.2	20.4
All	11	118	18.2	26.8	20.6	25.8

tions have been calculated two ways: by (1) giving equal weight to each data point, and (2) giving equal weight to each data set.

As some of the data sets have a large number of data points and some have very few, giving equal weight to each data point biases the results in favor of the large data sets. Giving equal weight to each data set appears to be a better way of evaluating the data in hand. Table 4 shows that the Shah correlation is more accurate in all ranges of $\Delta\rho$, though the Boelter et al. (1946) correlation is also satisfactory at $\Delta\rho > 0.02$ kg/m^3.

It is seen that deviations for $\Delta\rho < 0.02$ are significantly higher than those for $\Delta\rho > 0.02$. This is because the natural convection currents are weak at low density differences and the rate of evaporation is affected by sideways movement of air and stray air currents. These factors are largely unpredictable and therefore larger scatter is to be expected with any predictive technique. This is confirmed by the tests of Sharpley and Boelter (1938), who found that, at low density differences, scatter of measurements of repeated tests was about ±15%.

CONCLUSION

The Shah correlation, which is derived from theory, agrees well with a very wide range of data for evaporation from pools into quiet air. The data from 11 sources included pool sizes from 0.07 to 425 m^2, water temperatures from 7 to 94°C, air temperatures from 6 to 35°C, and humidity from 28 to 95%. Other published correlations show much inferior agreement with the same data. Therefore the Shah (1992) correlation is the most reliable among the available methods of prediction.

NOMENCLATURE

The SI units listed below are applicable throughout except where specifically noted otherwise in the text.

C	coefficient in evaporation formula, Equation (1)
E	rate of evaporation, kg/(m^2·h)
i_{fg}	latent heat of vaporization of water, kJ/kg
p	partial pressure of water vapor in air, Pa
t	temperature
u	air velocity, m/s
W	specific humidity of air, kg of moisture/kg of air
x	concentration of water vapor in air, kg/m^3

Δx	$= (x_w - x_r)$, kg/m^3
δ	deviation of prediction from measurement
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

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