

Methods for Calculation of Evaporation from Swimming Pools and Other Water Surfaces

Mirza Mohammed Shah, PE, PhD
Fellow/Life Member ASHRAE

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. The author has previously published formulas for the calculation of evaporation from occupied and unoccupied indoor swimming pools, which were shown to agree with all available test data. In this paper, evaporation from many types of water pools and vessels is discussed and formulas are provided for calculating evaporation from them. These include indoor and outdoor swimming pools (occupied and unoccupied), spent nuclear fuel pools, decorative pools, water tanks, and spills. Look-up tables are provided for simplifying manual calculations.

INTRODUCTION

This paper attempts to provide reliable methods for the calculation of evaporation from many types of water pools, tanks, vessels, and spills. The author has previously published formulas for the calculation of evaporation from occupied and unoccupied indoor swimming pools, which were validated with all available test data (Shah 1992, 2008, 2012a, 2013) and are widely used. The calculation of evaporation is also required for many other applications and situations. In this paper, in addition to the author's published correlations for indoor swimming pools, formulas and methods are also provided for the calculation of evaporation for the following:

- Outdoor occupied and unoccupied swimming pools
- Pools with hot water, such as spent nuclear fuel pools
- Decorative pools
- Pools used for heat rejection from refrigeration systems

- Vessels/tanks with low water level
- Water spills

The calculation methods presented are based on physical phenomena, theory, and test data.

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.

Mirza Mohammed Shah is an independent consultant, Redding, CT.

UNOCCUPIED INDOOR SWIMMING POOLS

Present Author's Method

Shah developed formulas for evaporation from undisturbed water surfaces, which starting with Shah (1981), went through several modifications (Shah 1990, 1992, 2002, 2008). The final version is in Shah (2012), according to which the evaporation rate E_0 is the larger of those given by the following two equations:

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

$$E_0 = b(p_w - p_r) \quad (2)$$

with $C = 35$ in SI units and $C = 290$ in I-P units, $b = 0.00005$ in SI and $b = 0.0346$ in I-P units.

Equation 1 is the evaporation due to natural convection effect. It was derived using the analogy between heat and mass transfer. The derivation is given in the Appendix. Equation 2 shows the evaporation caused by the air currents produced by the building ventilation system. This was obtained by analyzing the test data for negative density difference as shown in Figure 1. The reasoning was that as natural convection essentially ceases under such conditions, all the evaporation must be occurring due to forced convection. As noted by the *ASHRAE Handbook—HVAC Applications* (ASHRAE 2007), air velocities in typical swimming pools range between 0.05 and 0.15 m/s (10 to 30 fpm). The computational fluid dynamics (CFD) simulations by Li and Heisenberg (2005) of a large swimming pool showed very complex airflow patterns along the surface and height of the pool, but the velocities within 1 m (3 feet) of the water surface were also in this range. Equation 2 is therefore considered applicable to velocities up to 0.15 m/s (30 fpm).

This method was validated by comparison with test data from 11 sources in Shah (2012b). Table 1 gives the range of parameters in each of these data sets. In Shah (2008), the same database (except the data of Hyldegard [1990]) was also compared to the ten published correlations listed in Table 2. Table 3 gives the results of these data analyses. It is seen that the 113 data points were predicted by the Shah formulas with a mean absolute deviation of 14.5% giving equal weight to each data set. All the other correlations gave much inferior agreement with data; thus, the Shah method is the most reliable among available methods and therefore may be used for practical calculations.

For ease of calculation using the Shah method, Equations 1 and 2 and Tables 4 and 5 have been prepared. These tables give the evaporation rates at discrete values of temperature and humidity in the range that may occur in swimming pools. Evaporation at intermediate values can be obtained by linear interpolation.

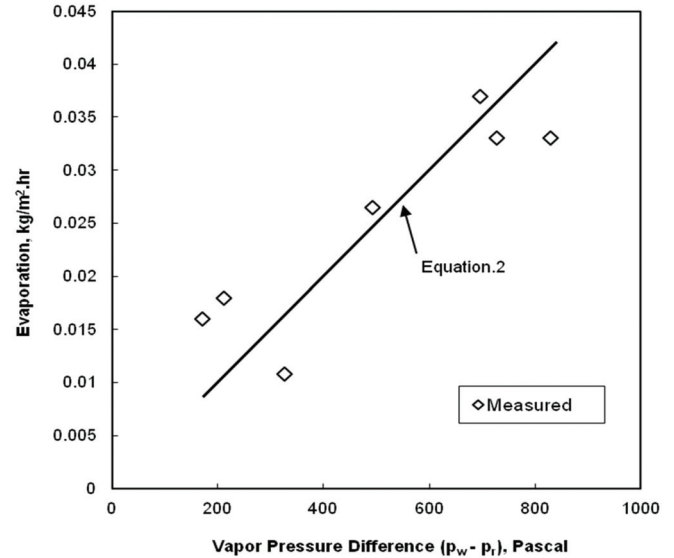


Figure 1 Analysis of data at negative density difference to obtain Equation 2 for forced convection evaporation in indoor pools. $1 \text{ Pa} = 2.953\text{E-}4 \text{ in. Hg}$, $1 \text{ kg/m}^2 \cdot \text{h} = 0.205 \text{ lb/ft}^2 \cdot \text{h}$.

Various Formulas for Undisturbed Water Pools

Many researchers performed tests in which air was blown or drawn over water surfaces and correlated their own test data in the form:

$$E = (a + bu)(p_w - p_r) \quad (3)$$

Where a and b are constants and u is the air velocity. Table 2 lists several such correlations. These are applied to indoor pools by inserting $u \approx 0$. Such formulas do not take into account natural convection, which depends on air density difference, and hence cannot be expected to be generally applicable to indoor pools in which natural convection effects are prevalent. This was pointed out by early researchers. For example, Himus and Hinchley (1924) performed tests on evaporation by natural convection as well as with forced airflow and gave formulas for both cases. They found that their forced convection formula extrapolated to zero velocity predicts three times their formula for natural convection. Lurie and Michailoff (1936) stated that forced convection equations should not be extrapolated to zero velocity as they will give erroneous results. Nevertheless, such formulas have continued to be proposed. The best known among such formulas is that of Carrier (1918) which is recommended by ASHRAE (2011) with correction factors called activity factors.

Many other researchers performed tests under natural convection conditions and correlated their own data by formulas of the form:

$$E = a(p_w - p_r)^n \quad (4)$$

Table 1. Range of Test Data for Undisturbed Water Pools with which Equations 1 and 2 and Other Formulas were Compared

Researcher	Pool Area		Water Temp.		Air Temp.		RH, %	$P_w - P_r$		$\rho_r - \rho_w$		Evaporation Rate,		Notes
	m ²	ft ²	°C	°F	°C	°F		Pa	in. Hg	kg/m ³	lb/ft ³	kg/m ² ·h	lb/h·ft ²	
Hyldegard (1990)	418	4493	26.1	79.0	28.5	83.3	37	1944	0.574	0.0134	8.4E-4	0.125	0.026	1
Bohlen (1972)	32	344	25.0	77.0	27.0	80.6	60	1029	0.303	0.0043	2.7E-4	0.052	0.011	1
Boelter et al. (1946)	0.073	0.78	24.0 94.2	75.2 201.6	18.7 24.7	65.7 76.5	64 98	1272 80156	0.375 23.7	0.022 1.0025	1.4E-3 0.062	0.082 21.07	0.016 4.2	2
Rohwer (1931)	0.837	9.0	7.1 16.5	44.5 61.7	6.1 17.2	43.0 63.0	69 78	247 638	0.073 0.188	0.0049 0.0080	3.1E-4 5.0E-4	0.010 0.040	0.0021 0.0082	2
Sharpley and Boelter (1938)	0.073	0.78	13.9 33.4	57.0 92.1	21.7	71.1	53	210 3786	0.062 1.12	-0.0049 0.088	-3.1E-4 5.5E-3	0.018 0.402	0.0036 0.0804	2
Biasin & Krumme (1974)	62.2	668	24.3 30.1	75.7 86.2	24.3 34.6	75.7 94.3	40 68	1010 2128	0.298 0.628	0.0007 0.030	4.4E-5 1.9E-3	0.030 0.154	0.006 0.0301	1
Sprenger (c. 1968)	200	2150	28.5	83.3	31.0	87.8	54 55	1422 1467	0.420 0.433	0.0070 0.0076	4.4E-4 4.7E-4	0.070 0.235	0.014 0.047	1
Tang et al. (1993)	1.13	12.1	25.0	77.0	20.0	68.0	50	2001	0.591	0.0433	2.7E-3	0.168	0.034	2
Recker (1978)	Note 3		23.0	73.4	25.5	77.9	71	493	0.145	-0.004	-2.5E-4	0.0265	0.054	1, 3
Smith et al. (1993)	404	4343	28.3	82.9	21.7 27.8	71.1 82.0	51 73	1127 1990	0.332 0.588	0.0150 0.0554	9.4E-4 3.5E-3	0.090 0.246	0.018 0.049	1
Doering (1979)	425	4568	25.0	77.0	27.5	81.5	28	2142	0.632	0.0153	9.4E-4	0.175	0.035	1
All Sources	0.073 425.0	0.78 4568	7.1 94.2	44.5 201.6	6.1 34.6	43.0 94.3	28 98	210 80156	0.062 23.7	-0.004 +1.002	-2.5E-4 +0.065	0.010 21.073	0.002 4.202	

Notes: 1. Field tests on swimming pool 2. Laboratory tests 3. Private pool, size not given

Where a and n are constants. Such formulas do not take into account density difference, which determines the intensity of natural convection, and hence cannot be expected to be generally applicable.

Many of the correlations of the type of Equations 3 and 4 are listed in Table 2. As is seen in Table 3, these give poor agreement with most data.

OCCUPIED INDOOR POOLS

Experience shows that evaporation from occupied pools is higher than from unoccupied pools. This increase is attributed to an increased area of contact between air and water due to waves, sprays, wet bodies of occupants, and wetting of deck. As deck area is usually comparable to the pool area, wetted deck represents the largest increase in air-water contact area. The air-water contact area is expected to increase with an increasing number of occupants. A number of formulas have

been published according to which the increase in evaporation compared to unoccupied pools depends only on the number of occupants (Hens 2009; Smith et al. 1999; Shah 2003). The basic assumption in these formulas is that the rate of evaporation from the increased air-water contact area is the same as from the pool area.

Shah (2013) pointed out that the rate of evaporation from the wetted deck area may not be the same as from the pool surface. Water spilled on the deck will quickly cool down, approaching the wet-bulb temperature. If the pool water temperature is higher than the air temperature, the rate of evaporation from the wetted deck will be much lower than from the pool surface as the density difference between air and water will be much lower at the deck, reducing the natural convection intensity. On the other hand, if the water and air temperatures are about equal, the rate of evaporation from the wetted deck will be comparable to that from the pool surface. Thus,

Table 2. Various Empirical Correlations for Undisturbed Water Pools

Author	Correlation, SI Units	Correlation, IP Units	Note
Carrier (1918)	$E = \frac{(0.089 + 0.0782u)(p_w - p_r)}{i_{fg}}$	$E = \frac{(95 + 0.425u)(p_w - p_r)}{i_{fg}}$	
Smith et al. (1993)	$E = \frac{0.76(0.089 + 0.0782u)(p_w - p_r)}{i_{fg}}$	$E = \frac{0.76(95 + 0.425u)(p_w - p_r)}{i_{fg}}$	
Biasin and Krumme (1974)	$E = -0.059 + 0.000079(p_w - p_r)$	$E = -0.0118 + 0.0535(p_w - p_r)$	
Rohwer (1931)	$E = 0.000252[1.8(t_w - t_r) + 3]^{2/3}(p_w - p_r)$	$E = 0.08(t_w - t_r + 3)^{2/3}(p_w - p_r)$	
Boelter et al. (1946)	For $\Delta x < 0.008$, $E = 5.71 \Delta x$ For $0.008 < \Delta x \leq 0.016$, $E = 4.88(-0.024 + 4.05795 \Delta x)$ For $\Delta x > 0.016$, $E = 38.2(\Delta x)^{1.25}$	For $\Delta x < 5E-4$, $E = 91.4 \Delta x$ For $5E-4 < \Delta x \leq 1E-3$, $E = 0.98(-0.024 + 64.92 \Delta x)$ For $\Delta x > 1E-3$, $E = 1222(\Delta x)^{1.25}$	Formula 1
Boelter et al. (1946)	$E = 0.0000162(p_w - p_r)^{1.22}$	$E = 0.065(p_w - p_r)^{1.22}$	Formula 2
Tang et al. (1993)	$E = 35(\Delta x)^{1.237}$	$E = 222(\Delta X)^{1.237}$	
Himus and Hinchley (1924)	$E = 0.0000258(p_w - p_r)^{1.2}$	$E = 0.089(p_w - p_r)^{1.2}$	
Leven (c. 1969)	$E = 0.0000094(p_w - p_r)^{1.3}$	$E = 0.073(p_w - p_r)^{1.3}$	
Box (1876)	$E = 0.0000778(p_w - p_r)$	$E = 0.054(p_w - p_r)$	

the increase in evaporation due to occupancy depends not only on the number of occupants but also the density difference between room air and the air in contact with the pool surface. Accordingly, Shah presented the following formula for evaporation from occupied pools:

For $N^* \geq 0.05$,

$$E_{occ}/E_0 = 1.9 - 21(\rho_r - \rho_w) + 5.3N^* \quad (5)$$

where N^* is the number of occupants per unit pool area. For $N^* < 0.05$, perform linear interpolation between E_{occ}/E_0 at $N^* = 0.05$ persons/m² (0.0046 persons/ft²) and $E_{occ}/E_0 = 1$ at $N^* = 0$. For $(\rho_r - \rho_w) < 0$, use $(\rho_r - \rho_w) = 0$. E_0 is calculated by the Shah (2012) method, larger of Equations 1 and 2.

In Figure 2, predictions of Equation 5 are plotted together with the predictions of the correlations of Hens (2009) and Smith et al. It is seen that at $\Delta\rho = 0.05$ kg/m³ (0.0031 lb/ft³), the predictions of Equation 5 and those of Smith et al. (1999) are almost identical. For $\Delta\rho = 0$, the predictions of Equation 5 are fairly close to the Hens formula. The formulas of Smith et al. and Hens were based entirely on their own data. The difference in their predictions is because of the different air and water conditions in their respective tests. Smith et al. (1993) report that water temperature was 28.3°C (83°F) and the air temperature varied from 21.6°C to 27.8°C (71°F to 82.0°F), with relative humidity from 51% to 73%; these conditions indicate that $\Delta\rho$ was high. In the tests reported by Hens, air

temperature was higher than water temperature; these conditions indicate that $\Delta\rho$ was small during the tests.

Equation 5 was compared to test data from four sources (all that could be found); the range of those data is listed in Table 6. The data were predicted with a mean absolute deviation of 18%, with deviations of 87% of the data within $\pm 30\%$. The same data were also compared with Shah (2003) phenomenological and empirical correlations, *ASHRAE Handbook—HVAC Applications* method (2007), and the formulas of Hens (2009), Smith et al. (1993), and VDI (1994). These correlations are listed in Table 7. The results of the comparison are in Table 8. While the Shah (2003) correlations performed fairly well, the others gave poor agreement. Thus Shah (2013), Equation 5, is easily the most reliable correlation for occupied pools.

For ease in hand calculations with Equation 5, Tables 9 and 10 list the density differences in the range of air and water conditions typical for indoor swimming pools. Hand calculations can be done easily using Table 9 or 10 together with Table 4 or 5, depending on the units being used.

Table 11 lists comparison of some individual data points for occupied and unoccupied indoor swimming pools with various formulas. It is seen that the Shah (2013) formula gives much better agreement with the data.

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

Data of	Number of Data Points	Percent Deviation From Correlation of Mean Absolute Average											Notes
		Biasin and Krumme	Box	Leven	Rohwer	Himus and Hinchley	Boelter et al., Formula 2	Boelter et al., Formula 1	Tang et al.	Carrier	Smith et al.	Shah	
Rohwer (1931)	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	34.2 12.0	
Bohlen (1972)	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	1.0 -1.0	
Smith et al. (1993)	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	18.7 -18.7	
Boelter et al. (1946)	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 (1938)	29	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	16.9 9.0	
Biasin and Krumme (1974)	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	6.1 6.1	1
	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	31.5 31.5	2
Tang et al. (1993)	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 (1978)	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	7.0 -7.0	
Doering (1979)	1	37.0 -37.0	4.8 -4.8	15.5 -15.5	NA	40.5 40.5	2.7 2.7	9.9 9.9	9.8 9.8	69.4 69.4	27.0 27.0	21.9 -21.9	
Hyldegard (1990)	1	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	5.0 -5.0	
All Data	113	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	22.7 ³ 10.2	4
		82.7 -82.7	40.6 33.3	39.3 26.5	67.6 67.6	76.6 76.6	34.5 29.3	24.9 2.2	36.5 33.5	121.8 121.8	71.3 67.7	14.5 2.0	5

Note: 1. Pool area 200 m². 2. Pool area 62.2 m². 3. Not evaluated. 4. Giving equal weight to each data point. 5. Giving equal weight to each data set.

Table 4. Evaporation from Unoccupied Indoor Swimming Pools by the Shah Formulas in SI Units

Water Temp., °C	Evaporation from Unoccupied Pool (E_0), Space Air Temperature, and Relative Humidity											
	25°C		26°C		27°C		28°C		29°C		30°C	
	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%
25	0.1085	0.0809	0.0917	0.0636	0.0732	0.0515	0.0639	0.0450	0.0583	0.0382	0.0523	0.0311
26	0.1333	0.1042	0.1171	0.0872	0.0997	0.0693	0.0806	0.0547	0.0679	0.0479	0.0620	0.0408
27	0.1597	0.1289	0.1433	0.1118	0.1262	0.0941	0.1081	0.0753	0.0885	0.0582	0.0723	0.0510
28	0.1877	0.1556	0.1711	0.1380	0.1539	0.1200	0.1360	0.1014	0.1171	0.0818	0.0968	0.0618
29	0.2174	0.1841	0.2006	0.1661	0.1831	0.1477	0.1651	0.1287	0.1463	0.1092	0.1268	0.0888
30	0.2491	0.2146	0.2319	0.1962	0.2142	0.1773	0.1959	0.1579	0.1771	0.1380	0.1575	0.1176

Table 5. Calculated Evaporation Rate from Unoccupied Pools at Typical Design Conditions by the Shah (2012a) Method in I-P Units

Water Temp., °F	Evaporation from Unoccupied Pool (E_0) Space Air Temperature and Relative Humidity											
	76°F		78°F		80°F		82°F		84°F		86°F	
	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%
76	0.0213	0.0159	0.0176	0.0120	0.0135	0.0099	0.0123	0.0085	0.0110	0.0069	0.0097	0.0053
78	0.0269	0.0211	0.0232	0.0173	0.0193	0.0133	0.0149	0.0106	0.0132	0.0091	0.0118	0.0075
80	0.0327	0.0266	0.0291	0.0228	0.0252	0.0188	0.0212	0.0146	0.0166	0.0114	0.0141	0.0097
82	0.0390	0.0326	0.0353	0.0287	0.0314	0.0246	0.0274	0.0204	0.0232	0.0160	0.0185	0.0122
84	0.0458	0.0391	0.0420	0.0350	0.0381	0.0309	0.0340	0.0266	0.0298	0.0222	0.0253	0.0176
86	0.0530	0.0461	0.0492	0.0419	0.0452	0.0377	0.0410	0.0333	0.0368	0.0288	0.0323	0.0241
88	0.0608	0.0536	0.0569	0.0494	0.0528	0.0450	0.0486	0.0405	0.0442	0.0358	0.0397	0.0311
90	0.0692	0.0618	0.0651	0.0574	0.0610	0.0529	0.0567	0.0482	0.0522	0.0435	0.0476	0.0386

Pool Occupancy Limits

According to the International Building Code 2006, the maximum allowable occupancy in swimming pools is 4.6 m² (50 ft²) of pool surface area per person. This code has been adapted in many parts of the world. In the U.S., each state and almost every town has its own code. Some of them have incorporated the International Building Code while some have not done so. Local authorities should be contacted to find the applicable regulations.

Recommended Calculation Procedure

The following calculation procedure is recommended:

- For unoccupied swimming pools, calculate evaporation with Equations 1 and 2 and use the larger of the two.
- For occupied swimming pools, calculate E_0 as above and then apply Equation 5.

OUTDOOR SWIMMING POOLS

Unoccupied Pools

Natural convection effects in outdoor pools will be the same as in indoor pools. The difference will be in the forced-convection effects. In indoor pools, airflow is due to building ventilation system, while airflow on outdoor pools is due to wind. If there were no obstructions such as trees and buildings, evaporation could be calculated using the analogy between heat and mass transfer considering the pool surface to be a heated plate. With this approach, Shah (1981) derived a simplified equation for evaporation due to wind velocity, which is given in the Appendix. That equation is applicable if there are no obstructions around the

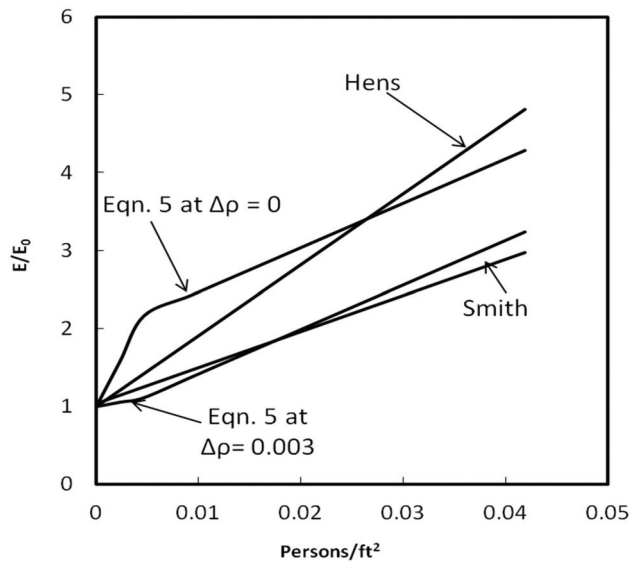


Figure 2 Comparison of the Shah formula (2013) Equation 5 with the correlations of Hens (2009) and Smith et al. (1999) at two values of air density difference, in lb/ft³, 1 lb/ft³ = 16 kg/m³, 1 ft² = 0.093 m².

pool. This is also the case for equations developed from wind tunnel tests. Most outdoor pools are located close to buildings and trees which distort the airflow streams. Hence, formulas developed from tests on actual swimming pools are preferable. The only one found in the literature is that by Smith et al. (1999) who measured evaporation from an unoccupied outdoor swimming pool and fitted the following equation to their test data:

$$E_0 = (C_1 + C_2 u)(p_w - p_a)/i_{fg} \quad (6)$$

Table 6. Range of Data for which the Shah (2013) Formula for Occupied Indoor Pools has Been Verified

Source	Pool Area, m ² (ft ²)	Persons, per m ² (per ft ²)	Air Temp., °C (°F)	RH, %	Water Temp., °C (°F)	$\rho_r - \rho_w$, kg/m ³ (lb/ft ³)	$(p_w - p_r)$, Pa (in. Hg)
Doering (1979)	425	0.082 (0.008)	27.5 (81.5)	33	25.0 (77)	0.0024 (0.00015)	1526 (0.45)
	(4575)	0.167 (0.017)	29.0 (84.2)	41		0.0153 (0.00096)	2141 (0.63)
Biasin and Krumme (1974)	64	0.016 (0.0015)	26.0 (78.8)	46	26.0 (78.8)	-0.0013 (-8 × 10 ⁻⁵)	1067 (0.31)
	(689)	0.325 (0.03)	30.0 (86.0)	72	30.0 (86.0)	0.0313 (0.0019)	2087(0.62)
Heimann and Rink (1970)	200	0.10 (0.0093)	31.0 (87.8)	54	28.5 (83.3)	0.007 (0.00044)	1422 (0.42)
	(2153)	0.325 (0.039)		55			
Hanssen and Mathisen (1990)	72	0.028 (0.037)	30.0 (86.0)	60	32.0 (89.6)	0.0312 (0.00195)	2084 (0.62)
	(774)	0.486 (0.045)		65		0.0421 (0.0026)	2377 (0.70)
All Data	64(689)	0.016 (0.0015)	26 (78.8)	32	25 (77)	-0.0013 (-8 × 10 ⁻⁵)	1067 (0.37)
	425(4575)	0.486 (0.045)	31 (87.8)	72	32 (89.6)	0.0421 (0.0026)	2377 (0.7)

Table 7. Various Correlations for Occupied Pools which Were Evaluated Together with Equation 5

Correlation of	SI Units	I-P Units
ASHRAE Handbook—HVAC Applications (2007)	$E = 0.000144(p_w - p_r)$	$E = 0.1(p_w - p_r)$
Smith et al. (1999)	$E = 0.0000106(1.04 + 4.3N^*)(p_w - p_r)$	$E = 0.0072(1.04 + 46.3N^*)(p_w - p_r)$
VDI (1994)	$E = 0.0000204(1 + 8.46N^*)(p_w - p_r)$	$E = 0.014(p_w - p_r)$
Hens (2009)	$E = 0.0000409(1 + 8.46N^*)(p_w - p_r)$	$E = 0.028(1 + 91N^*)(p_w - p_r)$
Shah (2003) Empirical	$E = 0.113 - 0.000079/F_U + 0.000059(p_w - p_r)$	$E = 0.0226 - 0.000016/F_U + 0.04(p_w - p_r)$
Shah (2003) Phenomenological	$E/E_0 = 3.3F_U + 1$ for $F_U < 0.1$ $E/E_0 = 1.3F_U + 1.2$ for $0.1 \leq F_U \leq 1$ $E/E_0 = 2.5$ for $F_U > 1$	$E/E_0 = 3.3F_U + 1$ for $F_U < 0.1$ $E/E_0 = 1.3F_U + 1.2$ for $0.1 \leq F_U \leq 1$ $E/E_0 = 2.5$ for $F_U > 1$

Table 8. Deviations of Various Formulas for Occupied Pools with Test Data

Data of	Evaluated Formulas						
	ASHRAE (2007)	VDI (1994)	Smith et al. (1999)	Hens (2009)	Shah (2003) Empirical	Shah (2003) Phenom.	Shah (2013) Equation 5
Doering (1979)	15.3	60.2	20.6	-42.8	-0.4	-24.3	-7.0
	17.2	60.2	21.5	42.8	6.0	29.1	23.9
Hanssen and Mathisen (1990)	-34.2	-8.6	-28.6	-51.0	-49.0	-27.0	-18.7
	34.2	26.4	28.6	51.0	49.0	27.0	20.1
Heimann and Rink (1970)	-4.5	32.7	16.6	-25.4	-8.1	-26.1	-5.5
	13.0	32.7	16.6	25.4	14.3	26.1	8.1
Biasin and Krumme (1974)	39.9	94.3	36.2	-38.8	32.7	-5.1	6.8
	44.4	94.3	37.8	38.8	36.2	23.6	17.9
All data	18.3	64.3	20.7	-39.7	8.9	-14.4	-1.1
	34.3	69.9	31.0	39.7	30.6	25.3	18.0

Note: For each data source, first line is arithmetic average deviation, second line is mean absolute deviation.

Table 9. Air Density Difference $\rho_r - \rho_w$ at Typical Swimming Pool Conditions in SI Units

Water Temp., °C	Density Difference $\rho_r - \rho_w$, kg/m ³ Space Air Temperature and Relative Humidity											
	25°C		26°C		27°C		28°C		29°C		30°C	
	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%
25	0.0185	0.0148	0.0135	0.0096	0.0084	0.0043	0.0034	0	0	0	0	0
26	0.0246	0.0209	0.0196	0.0157	0.0145	0.0104	0.0095	0.0051	0.0044	0	0	0
27	0.0308	0.0271	0.0258	0.0218	0.0207	0.0166	0.0156	0.0113	0.0105	0.0059	0.0054	0.0005
28	0.0370	0.0333	0.0320	0.0281	0.0270	0.0228	0.0219	0.0175	0.0168	0.0122	0.0116	0.0068
29	0.0434	0.0397	0.0384	0.0344	0.0333	0.0292	0.0282	0.0238	0.0231	0.0185	0.0180	0.0131
30	0.0498	0.0461	0.0448	0.0409	0.0397	0.0356	0.0347	0.0303	0.0295	0.0249	0.0244	0.0195

Table 10. Air Density Difference $\rho_r - \rho_w$ at Typical Pool Conditions in I-P Units

Water Temp., °F	Density Difference $\rho_r - \rho_w$, lb/ft ³ Space Air Temperature and Relative Humidity											
	76°F		78°F		80°F		82°F		84°F		86°F	
	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%	50%	60%
76	0.0011	0.0009	0.0008	0.0005	0.0004	0.0002	0.0001	0	0	0	0	0
78	0.0015	0.0013	0.0012	0.0010	0.0008	0.0006	0.0005	0.0002	0.0001	0	0	0
80	0.0020	0.0017	0.0016	0.0014	0.0013	0.0010	0.0009	0.0006	0.0006	0.0003	0.0002	0
82	0.0024	0.0022	0.0020	0.0018	0.0017	0.0014	0.0013	0.0011	0.0010	0.0007	0.0006	0.0003
84	0.0028	0.0026	0.0025	0.0022	0.0021	0.0019	0.0018	0.0015	0.0014	0.0011	0.0011	0.0008
86	0.0033	0.0031	0.0029	0.0027	0.0026	0.0023	0.0022	0.0020	0.0019	0.0016	0.0015	0.0012

In SI units, $C_1 = 235$, $C_2 = 206$, u is in m/s, p in Pa, i_{fg} in J/kg. In I-P units $C_1 = 70.3$, $C_2 = 0.314$, u is in fpm, p in in. of Hg, i_{fg} in Btu/lb.

The wind velocity was measured at 0.3 m (3 ft) above the water surface and the maximum was 1.3 m/s (264 fpm). There must have been strong natural convection effects as water temperature was always higher than the air temperature. Jones et al. (1994) report that during the companion unoccupied pool tests in this research program, water temperature was 29°C and the air temperature varied from 14.4°C to 27.8°C (58°F to 82°F), with relative humidity from 27% to 65%. Thus, the predictions of this formula at lower velocities do not represent forced-convection effects. Their measurements at 200 fpm (1 m/s) and higher velocity are likely to be free of natural convection effects. Further, considering that Equation 2 is valid up to a velocity of 0.15 m/s (30 fpm), the following equation is proposed for forced-convection effects.

$$E_0 = a(u/b)^{0.7}(p_w - p_a) \quad (7)$$

In SI units, $a = 0.00005$, $b = 0.15$ m/s. In I-P units, $a = 0.0346$, $b = 30$ fpm.

This equation is plotted in Figure 3 along with the Smith et al. correlation Equation 6. Also plotted in this figure is the following formula given by Meyer (1942) which is among the most verified for large reservoirs.

$$E = (a + bu)(p_w - p_a) \quad (8)$$

In SI units, $a = 0.000116$, $b = 0.000126$, and u in m/s. In I-P units $a = 0.0807$, $b = 0.000407$, and u in fpm.

It is seen that the proposed formulas agrees closely with Equation 2 at the velocity of 0.15 m/s (30 fpm) and with the formulas of Meyer and Smith et al. (1999) at higher velocities. As the Smith et al. (1999) measurements were only upto a velocity of 1.3 m/s (254 fpm), agreement with the Meyer formula at higher velocities gives confidence that Equation 7 can be used for a wide range of wind velocities.

Table 11. Comparison of Some Data Points for Occupied and Unoccupied Swimming Pools with Various Formulas

Source	Pool Area m ² (ft ²)	Air Temp. °C (°F)	Air RH, %	Water Temp. °C (°F)	Number of Persons	Measured Evaporation kg/m ² ·h (lb/ft ² ·h)	Percent Deviation From Formula of				
							ASHRAE (2011)	VDI (1994)	Smith et al. (1993,1999)	Hens (2009)	Shah (2013)
Biasin and Krumme (1974)	62.2 (669)	32.2 (90)	51.6	27.9 (82.2)	6	0.152 (0.031)	21.0	68.1	28.5	-39.0	0.3
		28.0 (82.4)	57.6	30.0 (86.0)	1	0.172 (0.035)	73.2	140.5	43.3	-43.3	14.9
		31.0	54.0	28.5	0	0.07	50.9	6.9	122.0	-14.0	6.0
Heimann and Rink (1970)	200 (2149)	31.0 (87.8)	55.0	28.5 (83.3)	20	0.175 (0.035)	17.0	62.5	27.3	-38.7	-7.3
		31.0 (87.8)	55.0	28.5 (83.3)	65	0.235 (0.048)	-12.9	21.0	57.2	-7.3	5.1
Doering (1979)	425 (4568)	27.5 (81.5)	34	25 (77.0)	35	0.212 (0.043)	30.5	81.3	34.6	-37.2	12.9
Hansen and Mathieson (1990)	72 (774)	30.0 (86.0)	63	32 (89.6)	27	0.60 (0.122)	-50.0	-30.5	-1.8	-40.8	-9.7
Hylgaard (1990)	418 (4493)	28.5 (83.3)	37.0	26.1 (79.0)	0	0.125 (0.026)	12.0	-20.7	64.7	-36.4	-5.0
Bohlen (1972)	32 (344)	27.0 (80.6)	60.0	25.0 (77.0)	0	0.052 (0.011)	42.3	0.9	110.8	-19.1	-1.0
Reeker (1978)	Not Given	25.5 (77.9)	71.0	23.0 (73.4)	0	0.026 (0.0054)	33.9	-5.1	95.7	-23.0	-7.0

Effect of Occupancy

Smith et al. (1999) report results of their tests on both indoor and outdoor swimming pools, occupied and unoccupied. They found no difference in the effect of occupancy on evaporation rate between indoor and outdoor pools. This is what would be expected from the physical phenomena involved. Hence, Equation 5 is also applicable to outdoor pools.

Effect of Solar Radiation and Radiation to Sky

Solar radiation adds heat to pool water and thus reduces the energy needed for heating the pool. Further, the pool loses heat by radiation to the sky, which has to be made up by additional heating. These heat gains and losses have to be taken into consideration in the calculation of pool energy requirements. As seen in the formulas above, the rate of evaporation depends only on the water temperature and air conditions. In heated pools, water temperature is maintained constant by the heating system, and, hence, loss or gain by radiation is not involved in the calculation of evaporation. For unheated pools, water temperature has to be calculated taking into consideration all

heat gains and losses, including those by radiation. The calculation of evaporation is then done using the calculated water temperature.

Recommended Calculation Procedure for Outdoor Pools

The following calculation procedure is recommended for outdoor swimming pools:

- For unoccupied pools, calculate evaporation by Equations 1, 2, and 7. Use the largest of the three.
- For occupied pools, calculate E_0 as above and then apply Equation 5.

POOLS CONTAINING HOT WATER

A notable example of pools with hot water is the pool for storing spent fuel in nuclear power plants. During normal operation, water temperature could be up to 50°C (122°F). If cooling for the pool is lost during an abnormal/accidental event, temperatures can rise to boiling point. The Shah formula for natural convection has been verified for water temperatures up to 94°C (201°F) Shah (2002). Figure 4 shows

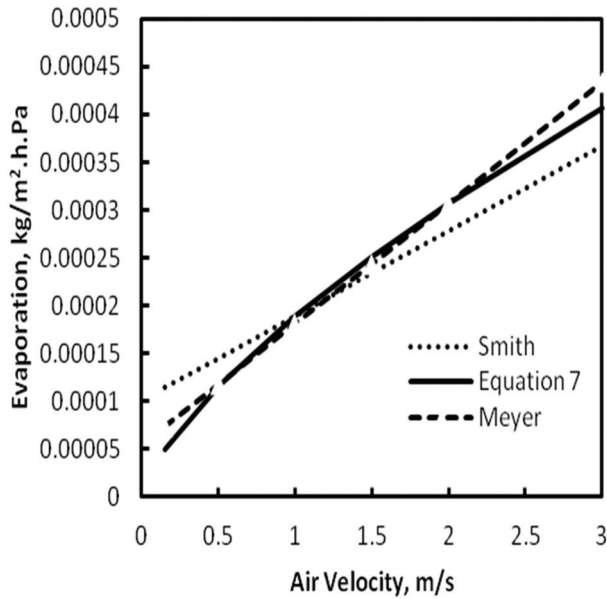


Figure 3 Comparison of the proposed new formula for evaporation, Equation 7, due to forced airflow, with the formulas of Smith et al. (1999) and Meyer (1944), $1 \text{ kg/m}^2 \cdot \text{h} = 0.205 \text{ lb/ft}^2 \cdot \text{h}$, $1 \text{ m/s} = 0.3048 \text{ ft/s}$.

the comparison of the data of Boelter et al. (1946) with the Shah formula. Air temperature during these tests varied from 19°C to 25°C (66.2°F to 77.0°F) and the relative humidity from 64% to 98%. The agreement is excellent throughout the range of water temperature.

Hugo (2013) provided the author with preliminary data from the fuel pool of a nuclear power plant (Columbia Generating Station). The pool dimensions were $10.4 \times 22.6 \text{ m}$ ($34 \times 40 \text{ ft}$). He measured the increase in evaporation as water temperature rose above 36.7°C (98°F). Air temperature was 25.5°C (78°F) and its relative humidity was 57%. Air velocity above the pool was 0.31 m/s (62 fpm). To get the total evaporation, evaporation at 36.7°C (98°F) was calculated by the Shah method described in the foregoing (largest of the values) and added to the measurements at other water temperatures. These were then compared with the Shah correlation as the larger of the free and forced convection evaporation, as calculated with Equation 1 and 7. The comparison of measured and predicted evaporation is shown in Figure 5. Good agreement is seen. Considering the good agreement with high temperature data of Boelter et al. (1946) and Hugo (2013), the Shah method can be confidently used for high-temperature pools.

For ease in hand calculations, Tables 12 and 13 have been prepared in SI and I-P units respectively. These list evaporation rates at discrete values of temperature and relative humidity, calculated as the larger of those from Equations 1 and 2. Calculations for intermediate values can be done by linear interpolation. Do not use these tables if air velocity is higher than 0.15 m/s (30 fpm).

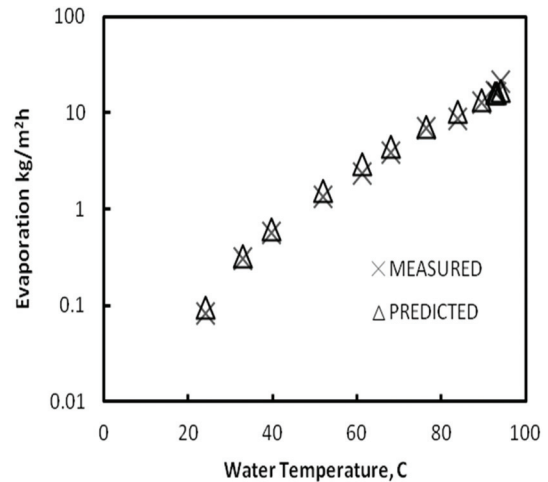


Figure 4 Comparison of the data of Boelter et al. (1946) with the predictions of the Shah correlation (2012a), Equations 1 and 2, $1 \text{ kg/m}^2 \cdot \text{h} = 0.205 \text{ lb/ft}^2 \cdot \text{h}$.

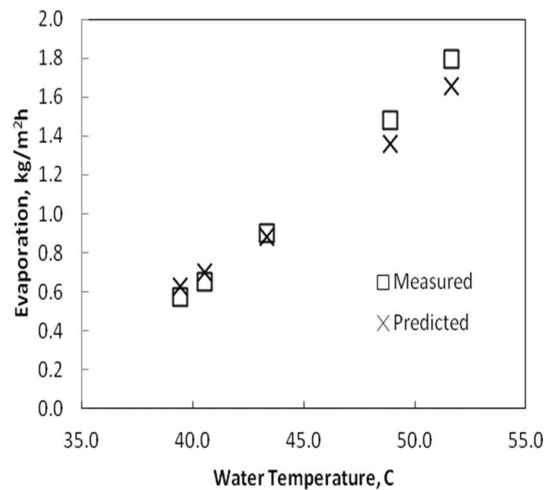


Figure 5 Comparison of data of Hugo (2013) for evaporation from a nuclear fuel pool with the Shah formula. Building air temperature 25.5°C (78°F), relative humidity 57%, $1 \text{ kg/m}^2 \cdot \text{h} = 0.205 \text{ lb/ft}^2 \cdot \text{h}$.

Recommended Calculation Procedure

The following procedure is recommended for calculation of evaporation from pools containing hot water:

- Calculation procedure is the same as for unoccupied swimming pools: calculate evaporation by Equations 1, 2, and 7 and use the largest of the three.
- Calculations may alternatively be done with Table 12 or 13 if air velocity does not exceed 0.15 m/s (30 fpm).

Table 12. Calculated Evaporation Rates at High Water Temperatures by the Shah Correlation (2012a), Larger of Equations 1 and 2, SI Units

Water Temp., °C	Air Temperature, °C, and Relative Humidity, %									
	30°C		35°C		40°C		45°C		50°C	
	30°C	70°C	30°C	70°C	30°C	70°C	30°C	70°C	30°C	70°C
35	0.443	0.246	0.350	0.116	0.236	0.023	0.138	0	0.096	0
40	0.707	0.485	0.608	0.332	0.495	0.165	0.033	0.033	0.184	0
45	1.057	0.816	0.951	0.644	0.830	0.448	0.691	0.232	0.530	0.047
50	1.516	1.26	1.403	1.072	1.274	0.853	1.126	0.603	0.956	0.325
55	2.113	1.845	1.992	1.643	1.855	1.405	1.698	1.128	1.517	0.809
60	2.879	2.603	2.752	2.390	2.607	2.137	2.441	1.839	2.251	1.489
65	3.856	3.576	3.721	3.352	3.569	3.088	3.396	2.775	3.198	2.403
70	5.088	4.809	4.948	4.578	4.790	4.306	4.661	3.983	4.407	3.598
75	6.632	6.358	6.486	6.123	6.323	5.847	6.140	5.520	5.932	5.130
80	8.550	8.288	8.400	8.053	8.234	7.778	8.049	7.453	7.840	7.066
85	10.92	10.67	10.76	10.44	10.60	10.17	10.41	9.859	10.21	9.487
90	13.81	13.60	13.66	13.38	13.49	13.12	13.31	12.83	13.12	12.48

Table 13. Calculated Evaporation Rates at High Water Temperatures by the Shah Correlation (2012a), Larger of Equations 1 and 2, I-P Units

Water Temp., °F	Air Temperature, °F, and Relative Humidity, %							
	90°F		100°F		110°F		120°F	
	30°F	70°F	30°F	70°F	30°F	70°F	30°F	70°F
100	0.111	0.063	0.087	0.029	0.058	0.004	0.031	0
110	0.182	0.128	0.157	0.088	0.27	0.043	0.092	0.006
120	0.278	0.220	0.251	0.175	0.22	0.122	0.183	0.062
130	0.408	0.346	0.379	0.297	0.345	0.238	0.306	0.168
140	0.58	0.516	0.549	0.463	0.513	0.399	0.471	0.323
150	0.805	0.740	0.772	0.684	0.735	0.617	0.691	0.536
160	1.097	1.032	1.063	0.975	1.023	0.905	0.978	0.821
170	1.471	1.408	1.435	1.35	1.395	1.28	1.349	1.195
180	1.946	1.887	1.91	1.829	1.869	1.760	1.823	1.677
190	2.544	2.491	2.507	2.435	2.467	2.37	2.423	2.291
200	3.290	3.246	3.254	3.194	3.215	3.134	3.173	3.064

VARIOUS POOLS AND TANKS

For pools in residences, condominiums, hotels, and therapeutic pools, the methods for indoor and outdoor swimming pools presented earlier in this paper are recommended. The *ASHRAE Handbook—HVAC Applications* (2007, 2011) recommends activity factors which give lower evaporation rates from such pools compared to public pools. The ASHRAE activity factors are based on experience and probably indicate that these pools have lower occupancy compared to public pools. While calculating evaporation with the present method, occupancy based on experience should be used.

Water pools are often provided inside and outside buildings to enhance aesthetics. In hot, dry climates, water pools provide evaporative cooling in naturally ventilated buildings. Outdoor pools are often used to provide cooling water for the condensers of refrigeration plants. Evaporation in all such pools can be calculated by the methods presented earlier for unoccupied indoor and outdoor swimming pools.

The same methods are recommended for various tanks and vessels containing water.

EFFECT OF EDGE HEIGHT OR LOW WATER LEVEL

If the water level is lower than the top edge of the pool or vessel, one will expect some impairment of natural convection currents and hence some reduction in evaporation. This effect will be expected to increase with increasing (δ/d) where δ is the edge height and d is the equivalent diameter of the vessel or pool. This possible effect has been investigated by several researchers.

Sharpley and Boelter (1938) measured evaporation into quiet air from a 0.305 m (1 ft) diameter pan. The water level was flush with top. Tests were also performed with water level 12.7 and 38.1 mm (0.5 and 1.5 in.) below the top edge. Thus, (δ/d) varied from 0 to 0.125. Sharpley and Boelter found no effect of liquid level variation. Hickox (1944) also did similar tests. His data do not show any clear effect of level variation.

Stefan (1884) measured evaporation from tubes of diameter 0.64 to 6.16 mm (0.025 to 0.24 in.) and depth below the rim of 0 to 44 mm (0 to 1.7 in.). He found the evaporation rate to be inversely proportional to the depth. Considering the larger tube, (δ/d) at 44 mm (17.3 in.) depth below the top would be 7.1. As noted earlier, reduction in evaporation at large (δ/d) is expected as inward and outward movement of natural convection streams of air will be hampered. At very large depths, evaporation will be entirely due to molecular diffusion.

For large values of (δ/d) , evaporation by forced convection will also be impaired as airstream will be unable to remove the air layers near the water surface.

In swimming pools, the water level is close to the top and hence there is no reduction in evaporation. For other types of pools and vessels in which water level is very low, the predictions by the Shah method will need to be corrected. Details of Stefan's tests are not available and no other test data were

found. Based on the results of Stefan (1884) mentioned earlier, the following is tentatively suggested as a rough guide:

$$\text{For } (\delta/d > 1), \quad E = E_{\text{shah}}(\delta/d) \quad \text{is } \geq E_{\text{md}} \quad (9)$$

Where E_{shah} is the evaporation rate by the Shah method and E_{md} is the evaporation by molecular diffusion. Methods to calculate evaporation by molecular diffusion are explained in text books as well as in Chapter 6 of the *ASHRAE Handbook—Fundamentals* (2013).

EVAPORATION FROM WATER SPILLS

Water spilled on the floor will cool down fairly quickly, approaching the wet-bulb temperature of air. If it reaches the wet bulb temperature, the difference of density between room air and the air at water surface will be zero, there will be no natural convection, and evaporation will be due to forced convection. Hence, the following simple method is suggested for approximately calculating evaporation rate from spills:

1. Assume water temperature to be equal to the wet-bulb temperature of air.
2. For spills inside buildings, use Equation 2 to calculate evaporation.
3. For outdoor spills, use Equation 7 to calculate evaporation.

More rigorous transient calculations may be done with a computer model that takes into consideration heat transfer between the floor and water together with heat and mass transfer between air and water. The Shah correlation may be incorporated into such a model.

SUMMARY OF RECOMMENDED CALCULATION METHODS

The calculation methods recommended in the foregoing are summarized in Table 14.

CONCLUSION

In this paper, methods for calculating evaporation from many types of pools and other water surfaces were presented and discussed. These include the author's published correlations for indoor occupied and unoccupied swimming pools. Also presented were methods for outdoor occupied and unoccupied swimming pools, hot-water pools such as nuclear fuel pools, decorative pools, tanks and vessels/containers, and water spills. These methods are based on theory, physical phenomena, and test data. A number of look-up tables were provided for easy manual calculations.

More tests to collect data on evaporation from swimming pools is highly desirable, especially for occupied pools as data from only four sources could be found.

Table 14. Summary of Recommended Calculation Methods

Application	Calculation Method	Notes
Indoor swimming pool, unoccupied	Use larger of Equations 1 and 2	Tables 4 and 5 may be used for manual calculations
Indoor swimming pool, occupied	Use Equation 5	Tables 9 and 10 may be used with Tables 4 and 5 for manual calculations
Outdoor swimming pool, unoccupied	Use largest of Equations 1, 2, and 7	—
Outdoor swimming pool, occupied	Use Equation 5	E_0 by the method for outdoor unoccupied pools
Various types of pools, indoor or outdoor	Same as for unoccupied swimming pools	For indoor hot-water pools, Tables 12 and 13 may be used for manual calculations
Vessels, tanks, containers	Same as for unoccupied swimming pools	If water level is very low, correct prediction with Equation 9
Water spills	Assume water is at wet-bulb temperature of air and then calculate as for unoccupied swimming pool	For more accuracy, perform computerized transient calculations considering all factors

ACKNOWLEDGEMENT

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NOMENCLATURE

- A = area of water surface, m^2 (ft^2)
- d = diameter or equivalent diameter of vessel/tank, m (ft). Equivalent diameter = $(A/0.785)^{0.5}$
- D = coefficient of molecular diffusivity, m^2/h (ft^2/h)
- E = rate of evaporation under actual conditions, $kg/m^2 \cdot h$ ($lb/ft^2 \cdot h$)
- E_{occ} = rate of evaporation from occupied swimming pool, $kg/m^2 \cdot h$ ($lb/ft^2 \cdot h$)
- E_0 = rate of evaporation from unoccupied pools, $kg/m^2 \cdot h$ ($lb/ft^2 \cdot h$)
- F_U = pool utilization factor, = $4.5 N^*$ ($42N^*$), dimensionless
- g = acceleration due to gravity, m/s^2 (ft/s^2)
- Gr = Grashof number, dimensionless
- i_{fg} = latent heat of vaporization of water, J/kg (Btu/lb)
- h_M = mass transfer coefficient, m/h (ft/h)
- L = characteristic length m (ft)
- N = number of pool occupants
- N^* = N/A , persons/ m^2 (persons/ ft^2)
- Nu = Nusselt number, dimensionless
- p = partial pressure of water vapor in air, Pa (in. Hg)
- Pr = Prandtl number, dimensionless
- Re_L = Reynolds number = $u\rho L/\mu$, dimensionless
- Sc = Schmidt number = $\mu/\rho D$, dimensionless

- Sh = Sherwood number, = $h_M L/D$, dimensionless
- u = air velocity, m/s (fpm)
- W = specific humidity of air, kg of moisture/ kg of air (lb of moisture/ lb of air)
- x = concentration of moisture in air, kg of water/ m^3 of air (lb of moisture/ ft^3 of air)
- Δx = $(x_w - x_r)$, kg/m^3 (lb/ft^3)

Greek Symbols

- δ = depth of water level below top edge, m (ft)
- μ = dynamic viscosity of air, $kg/m \cdot h$ ($lb/ft \cdot h$)
- ρ = density of air, mass of dry air per unit volume of moist air, kg/m^3 (lb/ft^3) (This is the density in psychrometric charts and tables)
- $\Delta\rho$ = $(\rho_r - \rho_w)$, kg/m^3 (lb/ft^3)

Subscripts

- a = of air away from the water surface
- H = heat transfer
- M = mass transfer
- r = at room temperature and humidity
- w = saturated at water surface temperature

APPENDIX

Derivation of Formula for Evaporation by Natural Convection

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 upwards.

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

$$E_0 = h_M \rho_w (W_w - W_r) \quad (\text{A1})$$

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

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

$$\text{Nu} = 0.14(\text{Gr}_H \text{Pr})^{1/3} \quad (\text{A2})$$

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

$$\text{Sh} = 0.14(\text{Gr}_M \text{Sc})^{1/3} \quad (\text{A3})$$

Gr_M is defined as (Eckert and Drake 1972)

$$\text{Gr}_M = \frac{\gamma g (W_w - W_r) L^3 \rho^2}{\mu^2} \quad (\text{A4})$$

where

$$\gamma = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial W} \right) \quad (\text{A5})$$

Equation A5 may be approximately written as

$$\gamma = \frac{\rho_r - \rho_w}{\rho (W_w - W_r)} \quad (\text{A6})$$

Combining Equations A4 and A6

$$\text{Gr}_M = \frac{g(\rho_r - \rho_w) L^3 \rho}{\mu^2} \quad (\text{A7})$$

Using Equation A7 and the definitions of Sh and Sc, Equation A3 becomes

$$\frac{h_M L}{D} = 0.14 \left[\frac{(\rho_r - \rho_w) g L^3}{\mu D} \right]^{1/3} \quad (\text{A8})$$

Combining Equations A1 and A8:

$$E_0 = 0.14 g^{1/3} D^{2/3} \mu^{-1/3} \rho_w (\rho_r - \rho_w)^{1/3} (W_w - W_r) \quad (\text{A9})$$

The value of $(D^{2/3} \mu^{-1/3})$ does not vary much over the typical range of room air conditions. Inserting a mean value, Equation A9 becomes:

$$E_0 = C \rho_w (\rho_r - \rho_w)^{1/3} (W_w - W_r) \quad (\text{A10})$$

with $C = 35$ in SI units and 290 in I-P units.

It is noteworthy that Equations A9 and A10 have been derived from theory without any empirical adjustments. Equa-

tion A10 was first published in Shah (1992); the detailed derivation was published in Shah (2008).

Derivation of Formulas for Evaporation by Forced Convection

For heat transfer during flow of air over a heated horizontal plate with turbulent flow, the mean Nusselt number for the plate is given by

$$\text{Nu} = (0.036 \text{Re}_L - 836) \text{Pr}^{1/3} \quad (\text{A11})$$

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

$$\text{Sh} = (0.036 \text{Re}_L - 836) \text{Sc}^{1/3} \quad (\text{A12})$$

The viscosity and Schmidt number of air change very little over the typical air conditions. Taking a mean value for them and substituting an empirical relation for the coefficient of diffusivity, the following formula is obtained for air-water in SI units.

$$E_0 = (0.0016t + 0.22)L^{-1} \quad (\text{A13})$$

$$[2.54(Lu\rho_a)^{0.8} - 256]\rho_w(W_w - W_a)$$

Where u is the free stream velocity in m/min and L is the length of pool in the direction of air in meters.

In I-P units, the equation is:

$$E_0 = (0.0092t + 2.07)L^{-1} \quad (\text{A14})$$

$$[3.5(Lu\rho_a)^{0.8} - 256]\rho_w(W_w - W_a)$$

Where u is in fpm and L is in feet..

The above derivation is from Shah (1981).

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