ASHRAE MEMORANDUM

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May 3, 2012

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RE: 2012 San Antonio Annual Conference Preprints

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If we do not hear from you by that date, we will assume the paper is correct and ready for inclusion into *ASHRAE Transactions*, Vol. 118, Part 2.

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Thank you for your time and contribution to ASHRAE literature.

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Calculation of Evaporation from Indoor Swimming Pools: Further Development of Formulas

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ABSTRACT

The author had earlier published formulas for evaporation from occupied and unoccupied indoor swimming pools. The formula for unoccupied pool was derived from the analogy between heat and mass transfer during natural convection. It was shown to be in good agreement with all published test data. However, it was applicable only to positive density difference (i.e. when the density of room air was greater than that of air at the pool surface). It has now been extended to apply to negative density differences. It has also been extended to include the case when air is forced over the surface of the pool to remove off gases. Calculation method is also provided for various types of occupied pools. Tabulations of calculated evaporation rates from unoccupied pools at typical design conditions.have been provided.

INTRODUCTION

Accurate calculation of evaporation from swimming pools is needed to ensure proper sizing of HVAC equipment as well as for the estimation of energy consumption. Unoccupied indoor swimming pools are one important application. Numerous empirical correlations have been presented for unoccupied swimming pools, the best known among which is the correlation of Carrier (1918). None of them has been found to be accurate beyond the data on which they were based (Shah 2002). ASHRAE Handbook (ASHRAE 2007) has provided multiplication factors (called activity factors) to be applied to the Carrier correlation to bring predictions closer to those experienced. However, attempts at such corrections cannot be fully successful as evaporation occurs mainly by natural convection while the Carrier formula does not include the parameters to take it into account. As was shown by Shah (2002, 2008), its agreement with fully occupied pool data is reasonable but shows poor agreement with data for unoccupied and partially occupied pools.

The present author presented a formula for evaporation from an undisturbed water pool into quiet air derived by the direct application of the analogy between heat and mass transfer (Shah 2002, 2008). It was shown to be in good agreement with almost all available test data. However, it is applicable only to positive air density difference (i.e. when the density of room air is larger than the density of air at the surface of water). There are situations in which the density difference is negative. The calculation methodology has now been modified to include such situations.

In recent years there has been a concern that gases given off the water surface have harmful effect on pool occupants. One of the ways proposed to counter this problem is to blow air along the pool surface to carry away these gases. This will increase the evaporation rate. A tentative formula has been developed for calculation with forced air flow.

In the following, the further development of the author's formulas to extend them to negative density differences, forced air flow, and various types of pools, is presented. Tables of calculated evaporation rates at typical design conditions are provided for the convenience of designers. The ASHRAE Handbook method is discussed first as it is widely used and is involved in the developments presented here.

The paper is written in SI units. the recommended calculation procedure is given In Inch-Pound units in the Appendix.

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ASHRAE HANDBOOK METHOD OF CALCULATION

The ASHRAE method is based on the following formula given by W. H. Carrier (1918)

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

This formula was based on tests done on an unoccupied pool across which air was blown. In the past, it was widely used for both occupied and unoccupied pools with or without forced air flow. Experience showed that it greatly overpredicted evaporation from unoccupied pools as well as from some occupied pools. ASHRAE therefore gave the multipliers (called activity factors) listed in Table 1 to correct the predictions of Equation 1. These activity factors are intended for use in sizing the dehumidification equipment and were based on consensus among ASHRAE Technical Committee members, not on any documented tests. Further, Equation 1 is modified in ASHRAE Handbook to the following form which is recommended for air velocities between 0.05 to 0.15 m/s.

$$E = 0.000144(p_w - p_a) \qquad (2)$$

SHAH FORMULA FOR UNOCCUPIED POOLS

By the use the well known relationship known as the analogy between heat and mass transfer during natural convection, Shah (2002, 2008) derived the following formula for evaporation from unoccupied pools.

$$E_0 = 35\rho_w(\rho_r - \rho_w)^{1/3}(W_w - W_r) \qquad (3)$$

For $(\rho_r - \rho_w) < 0.02$, predictions were found to be somewhat low. This was attributed to stray air currents and edge effects which become significant as the natural convection currents become weak. To account for these effects, a 15% increase in E_0 was specified for $(\rho_r - \rho_w) < 0.02$.

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

FURTHER DEVELOPMENT FOR POOLS WITH TYPICAL VENTILATION SYSTEMS

Physical Model

Evaporation occurs by two mechanisms:

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

These two mechanisms work independent of each other. It is postulated that all evaporation occurs by the stronger of the two mechanisms.

Evaporation by Natural Convection

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

Evaporation Due to Air flow by Ventilation System: Typical ventilation systems consist of supply diffusers on the ceiling near the wall on one side of the pool and return diffusers on the opposite side of pool. These produce air currents above the pool.

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

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

$$E_0 = 0.00005(p_w - p_r) \qquad (4)$$

Table 1. Activity Factors F_A for Various Pools to Be Used with the Carrier Equation, as Given in ASHRAE Handbook (2007)

Type of Pool	Air Temperature, C	Water Temperature, C	Relative Humidity,%	F_A
Baseline (unoccupied pool of any type)	Any	Any	Any	0.5
Residential pool	24 to 29	24 to 29	50 to 60	0.5
Condominium	24 to 29	24 to 29		0.65
Hotel	28 to 29	28 to 30		0.8
Public, school, competition	24 to 29	24 to 29		1.0
Therapeutic	27 to 29	29-35		0.65
Whirlpool/spa	27 to 29	36 to 40		1.0

Calculation Procedure

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

DEVELOPMENT OF FORMULA FOR FORCED AIR FLOW OVER POOLS

Evaporation rate can be expressed by the following equation:

$$E_0 = h_M \rho_w (p_w - p_r) / p_a \qquad (5)$$

For turbulent flow over a flat surface, using the analogy between heat and mass transfer, we may write (Shah 1981):

$$\frac{h_M L}{D} = Sc^{1/3}\left(0.036\left(\frac{VL\rho}{\mu}\right)^{0.8} - 836\right) \qquad (6)$$

The term '836' is negligible as the Reynolds numbers in turbulent flows are very large. Variations of air density in the typical range of conditions are small. Total air pressure varies very little. Then combining Equations 5 and 6:

$$E_0 = \text{function}\ (\mathrm{V}^{0.8}, \mathrm{L}^{-0.2}, \text{air properties}).\ (p_w - p_r) \qquad (7)$$

The air properties change vary little over the conditions of interest. Due to the small exponent of the pool width L and as the variations in pool widths are rather limited, L can be neglected as a variable. Then:

$$E_0 = \text{constant}.\ \mathrm{V}^{0.8}.\ (p_w - p_r) \qquad (8)$$

Smith et al. (1993) measured air velocity above a large indoor public swimming pool. The velocity varied from 0.035 to 0.05 m/s. Their test data agree well with the present author's method (Shah 2008). Hanssen and Mathisen (1990) measured velocity above the surface of a public pool and found it to average 0.15 m/s. ASHRAE Handbook recommends Equation 2 for velocities of 0.05 to 0.15 m/s. So Equation 4 may be considered to be applicable for velocities up to 0.15 m/s. At this velocity, air flow over the pool will be turbulent. Thus for higher velocities, we may write in accordance with Equation 8:

$$E_0 = 0.00005(V/0.15)^{0.8}(p_w - p_r) \qquad (9)$$

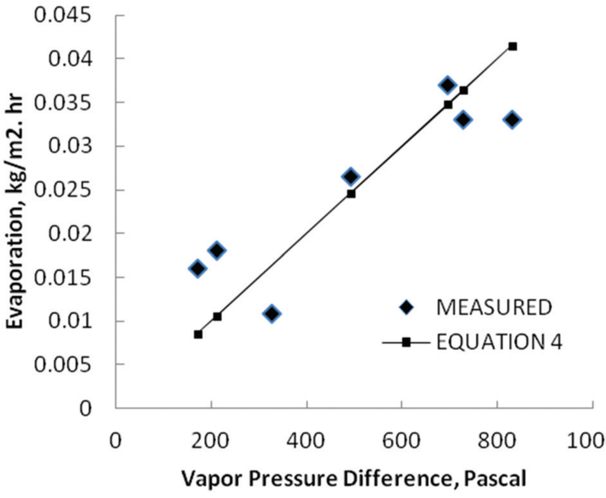

Figure 1 *Analysis of data for negative density difference, i.e.* $(\rho_a - \rho_w) < 0$.

The air velocities used for removing off-gases are likely to be less than 0.5 m/s. Analyzable data at such low velocities could not be found. Many formulas have been proposed for calculating evaporation with forced air flow. They take the form:

$$E_0 = C_1 + C_2 V \qquad (10)$$

The values of the constants C_1 and C_2 in various formulas are listed in Table 2. The Meyer formula was developed from data on large water reservoirs. The Carrier formula was based on data from a pool as noted earlier. The other formulas are from laboratory tests. The tests of Powell were for air velocities from 0.5 to 2.8 m/s. The other tests were at velocities of 1 m/s and higher. Formulas of the form of Equation 10 are not applicable at zero air velocity as then evaporation depends on density difference. Lurie and Michailoff (1936) noted that at zero air velocity, the formula of Himus and Hinchley (1924) for forced convection predicts three times the evaporation as the Himus-Hinchley formula for natural convection.

Figure 2 shows the comparison of these formulas with Equation 9. It is seen that at 1 m/s velocity, the prediction of Equation 9 are close to those by the Meyer, Carrier, and Powell-Griffiths equations. At 0.5 m/s, Equation 9 and the Powell-Griffiths formula predictions are almost the same. At higher velocities the agreement with the Meyer formula is quite good.

Thus Equation 9 has been verified down to velocity of 0.5 m/s. It seems likely than that it will be good for lower velocities also but it remains to be verified with test data.

OCCUPIED POOLS

Public Pools: The present author presented an empirical correlation that fitted all available data for occupied and

Table 2. Values of Constants by Various Researchers in the Equation $E_0 = C_1 + C_2 V$

Author	C_1	C_2
Carrier (1918)	0.000132	0.000116
Meyer (1942)	0.000116	0.000126
Powell and Griffith (1935)	0.000055	0.000136
Lurie and Michiloff (1936)	0.000168	0.000128

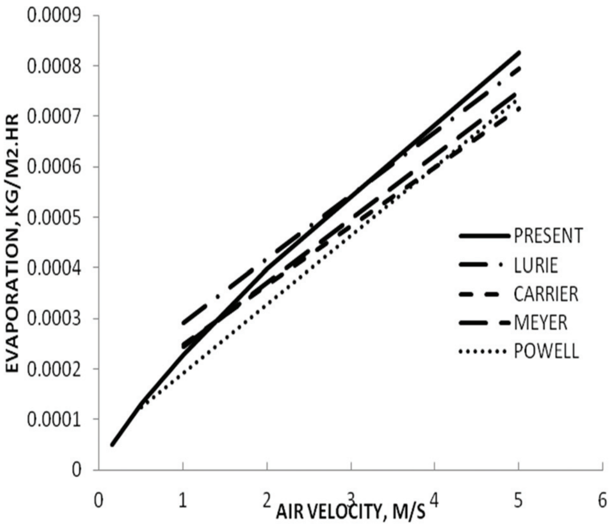

Figure 2 *Comparison of the present formula, Equation 9, with various published formulas at 1 Pa pressure difference.*

partially occupied public pools with a mean deviation of 16.2%. The ASHRAE Handbook method had a mean deviation of 36.2%. For fully occupied pools, the Shah formula may be written as:

$$E = 0.113 - 0.000079 + 0.000059(p_w - p_r) \tag{11}$$

Various Other Pools: As noted earlier, test data are not available for occupied pools other than public/competition pools. Until such data become available, the best information available are the ASHRAE Handbook activity factors listed in Table 1. Using these, multiplication factors (K) listed in Table 3 have been calculated. Using K, evaporation rate is calculated as:

$$E = K.\,E_0 \tag{12}$$

These K factors have been arrived at as follows. For unoccupied pools, the author's analytical procedure described above is very reliable as it is in good agreement with virtually all published data. In Table 1, F_A for unoccupied pools is 0.5. F_A for hotel pool is 0.8. Thus experience has shown that evaporation from hotel pools is 0.8/0.5 = 1.6 times that of an unoccupied pool. The K factors for residential and condominium pools have been calculated in the same way as the water and room temperatures for all these pools are in the same range and the activities of occupants are similar. However, this procedure may not be reliable for spas and therapeutic pools as the water temperatures are much higher and there is not much activity. Therefore K factors have not been given for these pools.

While the K factors have been derived from the activity factors, their use may be preferable as they are used with E_0 by the author's formula which has a firm theoretical basis and is thoroughly verified with test data. On the other hand, the Carrier formula does not have any basis for natural convection which is the predominant mode and does not include parameters for it.

Table 3. Author's Recommended Calculation Method for Pools of Various Types

Type of Pool	$K = E/E_0$	Note
Baseline (unoccupied pool of any type)	1.0	Based on F_A from ASHRAE Handbook. See Table 1
Residential pool	1.0	
Condominium	1.3	
Hotel	1.6	
Public, school, competition	NA	Use Equation 11

SUMMARY OF RECOMMENDED CALCULATION PROCEDURE

- For pools with typical ventilation systems, calculate E_0 by Equations 3 and 4 and use the larger of the two. (Table 5 provides calculated values of E_0 at most commonly used conditions.)
- For pools with forced air flow along the pool surface, calculate E_0 by Equations 3 and 9 and use the larger of the two values.
- Fully occupied competition/public pools, use the author's formula, Equation 11:
- For various other types of occupied pools, calculate as stated in Table 3.

VALIDATION OF THE RECOMMENDED CALCULATION PROCEDURE

The author had compared his original formulas for evaporation from occupied and unoccupied pools with a wide range of test data (Shah 2008). The data for unoccupied pools were from ten sources while those for occupied pools were from four sources. The range of those data is given in Table 4. No new analyzable data were found by literature search.

All those data were compared with the modified procedure recommended here. As the modifications affect mostly the data for air density difference less than 0.02 kg/m^3, only a small percentage of data were affected. Deviations of a few data points increased while those of a few others decreased. The overall deviations remained unchanged. All data for unoccupied pools were predicted with a mean deviation of 20.6% while the data for occupied pools were predicted with a mean deviation of 16.2%. Table 4 gives the range of data for which the recommended calculation procedure has been validated.

Table 4. Verified Range of Author's Formulas for Evaporation from Pools

	UNOCCUPIED POOLS	OCCUPIED POOLS
Pool area, m^2	0.073 to 425	64 to 1209
Water temperature, C	7 to 94	25 to 30
Air temperature, C	6 to 35	27 to 32
Air relative humidity,%	28 to 98	33 to 72
$(p_w - p_r)$, Pa	210 to 80,156	1,067 to 2,069
$(\rho_r - \rho_w)$, kg/m^3	-0.004 to +1.002	0.0013 to 0.218
Number of occupants	0	8 to 180

Table 5. Evaporation from Unoccupied Pools in SI Units at Typical Design Conditions Calculated from the Author's Formulas

	Evaporation from Unoccupied Pool (E_0) Space Air Temperature and Relative Humidity											
Water Temperature, C	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	0.0918	0.0636	0.0732	0.0515	0.0637	0.0450	0.0583	0.0382	0.0523	0.0311
26	0.1355	0.1042	0.1171	0.0872	0.0997	0.0693	0.0806	0.0547	0.0677	0.0479	0.0626	0.0479
27	0.1579	0.1290	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	0.0960	0.0618
29	0.2174	0.1841	0.2006	0.1661	0.1831	0.1477	0.1651	0.1287	0.1459	0.1092	0.1268	0.0888
30	0.2483	0.2146	0.2312	0.1962	0.2136	0.1773	0.1953	0.1579	0.1765	0.1380	0.1570	0.1176
31	0.2831	0.2474	0.2655	0.2285	0.2475	0.2091	0.2289	0.1892	0.2098	0.1688	0.1900	0.1480
32	0.3192	0.2825	0.3013	0.2631	0.2829	0.2432	0.2639	0.2228	0.2445	0.2019	0.2244	0.1805
39	0.6461	0.6035	0.6256	0.5808	0.6045	0.5575	0.5827	0.5334	0.5604	0.5087	0.5379	0.4833
40	0.7051	0.6617	0.6842	0.6386	0.6627	0.6148	0.6405	0.5903	0.6177	0.5655	0.5943	0.5391

APPLICATION TO OUTDOOR POOLS

All discussions till now have been for indoor pools. As seen in Figure 2, the proposed formula for evaporation by forced convection agrees well with many correlations for forced flow at air velocities of 1 m/s and higher. The Meyer formula is based on extensive measurements on wind exposed reservoirs. It therefore appears likely that the calculation procedure recommended here for indoor pools with forced air flow may also be applicable to outdoor pools. This remains to be checked by comparison with test data.

SUMMARY AND DISCUSSION

The author's formula for unoccupied indoor pools has been extended to include conditions when the density of air in contact with water surface is higher than that of room air. The extended formula has been verified by comparison with all published test data from ten sources.

A tentative formula has been developed for the case when air is blown along the surface of pool to remove off gases. This formula agrees well with several published correlations for velocities of 0.5 m/s and higher. It remains to be verified for lower velocities as analyzable data were not available.

A method has been developed for calculating evaporation from various types of occupied pools for which no test data are available. This consists of multiplication factors derived from the experience-based activity factors in the ASHRAE Handbook (2007), to be used with the author's formula for unoccupied pools. This method may be more reliable as the unoccupied pool formula is well-verified and has a firm theoretical basis.

Tables have been provided that give rate of evaporation from unoccupied pools at typical design conditions. These make it easier to perform design calculations.

NOMENCLATURE

The SI units given below apply for all equations in this paper except for the Appendix.

D = Coefficient of molecular diffusivity, m^2/h
E = Rate of evaporation from occupied pools, kg/m^2h
E_0 = Rate of evaporation from un-occupied pools, kg/m^2h
i_{fg} = Latent heat of vaporization of water, kJ/kg
h_M = Mass transfer coefficient, m/h
K = Multiplication factor in Equation 12, dimensionless
L = Characteristic length (i. e. width) of water pool, m
p = Partial pressure of water vapor in air, Pascals
p_a = Total pressure of air, Pascal
Sc = Schmidt number = $\mu/\rho D$, dimensionless
V = Air velocity, m/s
W = specific humidity of air, kg of moisture/kg of air
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)

Subscripts

w = Saturated at water surface temperature
r = At room temperature and humidity

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APPENDIX

RECOMMENDED CALCULATION METHOD IN I-P UNITS

All equations in the paper are given in SI units. In the following, the recommended calculation procedure is given in Inch-Pound units.

For unoccupied pools of all types with typical ventilation systems, calculate evaporation by Equations A1 and A2 and use the larger of the two.

$$E_0 = 290\rho_w(\rho_r - \rho_w)^{1/3}(W_w - W_r) \quad \text{(A1)}$$

$$E_0 = 0.0346(p_w - p_r) \quad \text{(A2)}$$

Calculated values of E_0 at commonly used design conditions are listed in Table A1.

For unoccupied pools with forced air flow over the pool, calculate evaporation with Equations A1 and A3 and use the larger of the two.

$$E_0 = 0.0346(V/30)^{0.8}(p_w - p_r) \quad \text{(A3)}$$

For fully occupied public, school, and competition pools, use Equation A4.

$$E = 0.023 - 0.0000162 + 0.041(p_w - p_r) \quad \text{(A4)}$$

For various types of pools listed in Table 3, calculate by Equation A4, E_0 calculated as described above or read from Table A1.

$$E = \mathrm{K}.\ E_0 \quad \text{(A5)}$$

The units for the above equations are:

E, E_0 = $lb/hr.\ ft^2$
K = Dimensionless
p_w, p_r = inches of Hg
V = ft/min
W = lb/lb
ρ_r, ρ_w = lb/ft^3

Table A1. Calculated Evaporation Rate from Unoccupied Pools at Typical Design Conditions By the Author's Method in Inch-Pound Units

Water Temperature, 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	0.0211	0.0159	0.0176	0.0120	0.0135	0.0099	0.0123	0.0085	0.0110	0.0069	0.0097	0.0053
78	0.0270	0.0211	0.0232	0.0173	0.0193	0.0133	0.0149	0.0106	0.0132	0.0091	0.0119	0.0075
80	0.0328	0.0266	0.0291	0.0228	0.0252	0.0188	0.0212	0.0146	0.0166	0.0114	0.0141	0.0098
82	0.0390	0.0326	0.0353	0.0287	0.0315	0.0245	0.0274	0.0204	0.0233	0.0160	0.0185	0.0110
84	0.0458	0.0391	0.0420	0.0351	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	0.0451	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
102	0.1335	0.1250	0.1289	0.1199	0.1241	0.1147	0.1192	0.1093	0.1142	0.1037	0.1088	0.0979
104	0.1469	0.1383	0.1422	0.1333	0.1374	0.1279	0.1324	0.1222	0.1272	0.1165	0.1219	0.1106