CALCULATING EVAPORATION FROM POOLS AND TANKS

Supported by field and laboratory data, modified formula accurately calculates evaporation from swimming pools and other horizontal water surfaces

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Calculation of evaporation from water pools and tanks containing water is needed for the design of both HVAC systems and various processes. Examples of water pools include swimming pools and pools for storing nuclear fuel in power plants. A variety of vessels and tanks with exposed water surfaces are used in the chemical and mechanical engineering industries.

In a recent article,[1] the author reviewed the available methods for calculating evaporation from swimming pools and presented a new formula for this purpose. In this article, a slightly modified version of that formula is presented and is shown to agree with test data that include water temperatures up to 202 F. All discussions in this article are for evaporation into quiet air; forced air flow is not considered.

Available formulas

Most reference works used by HVAC engineers recommend the following formula:

$$M/A = (95 + 0.425V) \times (p_w - p_a)/Y \qquad (1)$$

[1]*Superscript numerals refer to the references listed at the end of this article.*

Nomenclature

A = area of water surface, sq ft
B = molecular mass diffusion coefficient, sq ft per hr
D = density of air, lb of dry air per cu ft of mixture
d = density of air, lb of air-water mixture per cu ft of mixture
d_m = $(d_a + d_w)/2$
F_a = activity factor, dimensionless (F_a = 1 for unoccupied swimming pools and other quiet water surfaces)
g = acceleration due to gravity, ft per hr^2
L = length of pool, ft
M = evaporation rate, lb per hr
p = partial pressure of moisture in air, in. Hg
Ra = Raleigh number, $(d_a - d_w)gL^3/(UB)$, dimensionless
V = air velocity, fpm
t_m = mean of room air and pool water temperatures, F
U = dynamic viscosity of air, lb per hr ft
W = humidity ratio, lb of water per lb of dry air
w = humidity ratio, lb of water per lb of water-air mixture
Y = latent heat of water at pool temperature, Btu per lb

Subscripts

a = air at room conditions
w = saturated air at pool water temperature

This empirical formula was presented by W. H. Carrier in 1918.[2] It was stated to be based on his own tests on unoccupied pools. However, the most recent *ASHRAE Handbook*[3] states that this formula is applicable to occupied swimming pools; evaporation from unoccupied pools may be about half of that predicted by this formula. Earlier editions of *ASHRAE Handbooks* had recommended it without any reference to occupancy.

Numerous other formulas similar to Equation 1 have been presented. Rohwer[4] and Himus and Hinchley[5] measured evaporation from pools exposed to forced air flow as well as from pools exposed to quiet air. To the data for forced air flow they fitted formulas similar to Equation 1. However, these formulas did not agree with their data for zero air velocity. This disagreement is to be expected. In the absence of forced air flow, air movement occurs due to natural convection currents caused by the density difference between the light air near the water surface and the heavier room air above. Formulas like Equation 1 do not contain any factor for natural convection effects and hence cannot be generally successful in the absence of forced air flow.

The author used the analogy between heat and mass transfer to develop the following dimensionless formula for evaporation to quiet air:[6]

$$M/A = C\,Ra^n\, d_m (w_w - w_a) \times B/L \quad (2)$$

The values of C and n are respectively 0.14 and 0.33 for turbulent convection and 0.54 and 0.25 for laminar convection. All air properties are taken at the mean of room air and water surface temperatures.

As most practical HVAC engineers are not familiar with heat and mass transfer terminology, they would have difficulty in directly using Equation 2 for calculations. The author, therefore, gave the following simplified version for turbulent convection, which is the mode in almost all practical situations:[6]

$$M/A = 702\,(0.00087t_m + 0.192)^{2/3} d_m \times (d_a - d_w)^{1/3} (w_w - w_a) \quad (3)$$

This formula is somewhat inconvenient to use as the values of d and w are not listed in psychrometric tables. Therefore, the author further simplified it in developing the following version for swimming pools:[1]

$$M/A = 290 F_a D_a (D_a - D_w)^{1/3} \times (W_w - W_a) \quad (4)$$

F_a is the activity factor given by:

$$F_a = 1 + 15N/A \quad (5)$$

If Equation 5 predicts $F_a < 1.25$, use $F_a = 1.25$ if $N = 1$; otherwise, use $F_a = 1$. This formula was shown to agree with some field data. In the discussions on this article,[7] agreement with additional field data from swimming pools, as well as some laboratory data, was reported. These discussions also confirmed that the widely used Carrier formula greatly overpredicts evaporation from unoccupied swimming pools.

General-use formula

As is clear from the foregoing discussions, it may be considered well-established that for unoccupied swimming pools, the Carrier formula (Equation 1) grossly overpredicts while Equation 4 gives reasonably good predictions of evaporation. The situation with high-temperature water tanks and pools remains to be investigated.

Analysis of laboratory data on evaporation from water tanks at 43 to 202 F, as well as field data from swimming pools, showed that the following formula gives good agreement over the entire range:

$$M/A = 290 F_a D_w (D_a - D_w)^{1/3} \times (W_w - W_a) \quad (6)$$

The only difference between Equation 6 and Equation 4 is that the latter uses D_w rather than D_a outside the parentheses. For swimming pool conditions, the difference between D_w and D_a is negli-

TABLE 1—Comparison with the data of Boelter *et al*[8] for a 1 ft diameter tank.

Run number	Water temp., F	Room air: Temp., F	Room air: RH, percent	Evaporation, lb per hr sq ft: Measured	Shah Equation 6	Carrier Equation 1
1	75.2	71.9	64	0.0168	0.0165	0.022
8	91.2	72.5	73	0.0637	0.0660	0.080
13	103.6	75.1	74	0.1157	0.1280	0.135
17	125.4	76.5	88	0.2748	0.3200	0.286
21	142.1	79.3	83	0.4845	0.6000	0.483
26	154.4	72.8	88	0.7870	0.9200	0.690
35	155.9	67.7	95	0.8730	0.9600	0.730
44	169.7	70.2	98	1.4010	1.4500	1.030
47	148.7	65.6	91	0.7150	0.6500	0.515
52	164.3	71.8	91	1.1260	1.1500	0.950
55	182.9	76.5	59	1.7650	2.1200	1.420
60	193.1	70.7	77	2.6500	2.8000	1.780
65	199.0	69.4	96	3.3200	3.2500	2.010
72	201.6	66.1	95	4.3200	3.4800	2.120
80	199.7	67.2	98	3.2720	3.2600	2.040

TABLE 2—Comparison with the data of Sharpley and Boelter[9] for a 1 ft diameter tank evaporating into air at 71F dry bulb and 53 percent RH.

Run number	Water temperature, F	Evaporation, lb per hr per sq ft: Measured	Shah Equation 6	Carrier Equation 1
10	80.2	0.03590	0.04100	0.0570
21	85.3	0.05200	0.05860	0.0730
30	70.8	0.01220	0.01570	0.0320
36	73.5	0.01930	0.02220	0.0380
40	65.9	0.00678	0.00550*	0.0210
41	91.6	0.08230	0.08500	0.0950
47	92.2	0.07400	0.08800	0.1000
51	68.6	0.00705	0.01000	0.0270
59	57.0	0.00361	0.00361*	0.0057

*$D_a < D_w$ • $(D_w - D_a)$ used in Equation 6.

TABLE 3—Comparison with the data of Rohwer[4] for evaporation from a 3 by 3 ft pool.

Air dry bulb temperature, F	Water temperature, F	$p_w - p_a$, in. Hg	Evaporation, lb per hr per sq ft: Measured	Shah Equation 6	Carrier Equation 1
59.2	59.7	0.1660	0.00399	0.00254	0.00977
60.8	59.7	0.1080	0.00849	0.00601	0.01502
61.7	60.2	0.0095	0.00206	0.00169	0.00905
62.9	61.2	0.1000	0.00241	0.00107	0.00905
62.9	61.7	0.1900	0.00195	0.00616	0.01719
47.0	48.3	0.0770	0.00273	0.00278	0.00697
47.0	47.8	0.0880	0.00388	0.00305	0.00796
44.4	46.6	0.1230	0.00646	0.00527	0.01113
43.0	45.5	0.1070	0.00622	0.00461	0.00968
44.0	44.9	0.0780	0.00332	0.00269	0.00706
43.9	44.7	0.0730	0.00387	0.00232	0.00660

the SI units are widely used, SI versions of the proposed formulas, Equations 5 and 6, are given below:

$$F_a = 1 + 1.4N/A \quad (5)$$

where A is in sq m.

$$M/A = 35F_a D_w (D_a - D_w)^{1/3} \times (W_w - W_a) \quad (6)$$

where M is in kg per hr, D is in kg per cu m, and W is in kg per kg.

gible. For undisturbed water surface, $F_a = 1$. For swimming pools, F_a is calculated by Equation 5. For other pools and tanks with disturbed water surfaces—for example, agitated tanks—F_a is likely to be greater than 1, but information on this is not presently available.

Comparison with data

Tables 1 through 3 compare the Carrier formula (Equation 1) and the present formula (Equation 6) with representative data from laboratory studies on water pools with undisturbed water surfaces (F_a = 1). It is seen that at water temperatures typical of swimming pools, the Carrier formula grossly overpredicts evaporation; at high water temperatures, it underpredicts. The new formula gives reasonable agreement throughout the range. The results with the basic theoretical formula (Equation 2) were also satisfactory except that at very small density differences, it predicted low.

For the temperatures and relative humidities prevalent in swimming pool installations, the difference between D_a and D_w is negligible. Hence, all evidence[1,9] supporting Equation 4 also supports Equation 6.

If the density of room air is lower than the density of saturated air at water surface, there can be no natural convection, and hence Equation 6 is not applicable. However, evaporation continues at a lower rate by other mechanisms, such as molecular diffusion and edge effects, as long as $W_w > W_a$. In the absence of any other method, Equation 6 may be used with $(D_w - D_a)$ instead of $(D_a - D_w)$. As seen in Table 2, this procedure gave good agreement with a couple of data points, but this may be a mere coincidence.

Conclusion

In the foregoing, it has been shown that the new formula, Equation 6, gives good agreement with field data from swimming pools as well as laboratory data from three sources for water tanks with water temperatures ranging from 43 to 202 F. The widely used Carrier formula grossly overpredicts evaporation at low water temperatures and underpredicts at high water temperatures. Hence, Equation 6 is preferred and recommended for general use for swimming pools as well as other horizontal water surfaces, such as in vessels and tanks. Further research is needed to develop values of F_a for disturbed water surfaces. Ω

References

1) Shah, M. M., "Calculation of Evaporation from Swimming Pools," *Heating/Piping/Air Conditioning*, December 1990, p. 103-105.

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8) Boelter, L. M. K., H. S. Gordon, and J. R. Griffin, "Free Evaporation into Air of Water from a Free Horizontal Quiet Surface," *Industrial Engineering Chemistry*, Vol. 38, No. 6, June 1946, p. 596-600.

9) Sharpley, B. F., and L. M. K. Boelter, "Evaporation from Water into Quiet Air from a One-Foot Diameter Surface," *Industrial Engineering Chemistry*, Vol. 30, No. 10, October 1938, p. 1125-1131.

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Firms and people

The **Air-Conditioning and Refrigeration Institute** has organized a cooperative industry program to find acceptable alternatives to replace HCFC-22 in major air conditioning and refrigeration applications. The **ARI Refrigerants Evaluation Program** will entail extensive cooperative testing by manufacturers, with the findings to be made available to government agencies and the public.

ARI has also initiated a performance certification program for refrigerant recovery and recycling equipment. **ETL Testing Laboratories** is the performance testing verification source for participating manufacturers.

David W. Blevins, PE, has been named senior associate at **Dewberry & Davis,** architectural and engineering firm, Fairfax, Va.

Kenneth Wohlfarth, Mechanical Services, Inc., and **John J. Owens,** Owens Services Corp., have been appointed chairman of the board of managers and member of the board of managers, respectively, of the **Mechanical Service Contractors of America.**

Edward A. Sears Associates, mechanical, electrical, and energy management systems design firm, Manhattan, has named **Maurice W. Jones, PE,** director, administration and marketing services, and **Anthony D. Spezza,** director of the HVAC Dept.

Keith J. Kempski and **David E. Knebel, PE,** have joined the **Thermal Storage Applications Research Center** as associate director, seminars and workshops, and associate director, research, respectively.