DE-13-040

# New Correlation for Prediction of Evaporation from Occupied Swimming Pools

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

## ABSTRACT

*Well-verified methods for calculating rate of evaporation from swimming pools are not available. A new correlation is presented here which shows good agreement with all available data for partially and fully occupied swimming pools. Data from four studies (all that could be found) are correlated with a mean absolute deviation of 18%. Several other published correlations were also tested against the same data and gave much larger deviations. The new correlation will help in correct sizing of HVAC equipment and performing accurate energy consumption calculations.*

## INTRODUCTION

Experience has shown that evaporation from swimming pools increases with the number of occupants and their activity. The ventilation/dehumidification systems have to be designed to be able to remove the evaporated moisture so that humidity does not exceed safe limits. The design equipment capacity has to match the evaporation which occurs at maximum occupancy. However, pools are partially occupied for much of the time that they are in use. Further, pools are totally unoccupied for much of the time. Thus, for calculating energy consumption and for designing control strategies, the rate of evaporation at partial occupancy also needs to be calculated.

For calculating evaporation from unoccupied pools, Shah (2012) has presented a method which agrees with all published test data. Many formulas for calculating evaporation from occupied pools have been published, including two by Shah (2003). While the Shah (2003) formulas showed reasonable agreement with available data, it was felt that better accuracy was needed. The research reported here was undertaken to fulfill this need. A new correlation has been developed that shows good agreement with available test data from four sources. In the following, the new correlation is presented together with its comparison with test data. Other published correlations are also discussed.

This paper is written using SI units. Presentation in I-P units is in the Appendix at the end of the paper.

### Formulas for Evaporation from Unoccupied Pools

Most formulas for evaporation from occupied pools predict $E/E_0$, the ratio of evaporation from occupied pool to that from unoccupied pool. Hence, use of the occupied pool formulas requires the calculation of evaporation from unoccupied pools. Therefore, this topic is briefly discussed here.

The vast majority of formulas for unoccupied pools are of the form

$$E_0 = B\,(p_w - p_a) \tag{1}$$

The factor $B$ is a constant in many formulas, while in some it takes the form

$$B = C_1 + C_2 V \tag{2}$$

where $C_1$ and $C_2$ are constants and $V$ is the air velocity. For indoor pools, $V$ is considered 0 or given a low value. Such formulas were obtained by curve fitting to the researchers' own data. The best known among such formulas is that of Carrier (1918).

The method given by Shah (2012) is based on physical phenomena. According to him, evaporation rate is the larger of those given by the following two equations:

---

**Mirza Mohammed Shah** is a consultant in Redding, Connecticut.

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

$$E_0 = 0.00005\ (p_w - p_r) \tag{4}$$

Equation 3 represents evaporation by natural convection caused by density difference between the light-saturated air at water surface and the heavier room air; it was obtained by the use of the analogy between heat and mass transfer. Equation 4 gives the evaporation due to convection by air currents caused by the building ventilation system; it was obtained by analyzing test data for negative density differences. This method was shown to give good agreement with all published test data, while the correlations of the Equation 1 type showed poor agreement with the same data.

## AVAILABLE METHODS FOR CALCULATING EVAPORATION FROM OCCUPIED POOLS

The most widely used method is the following formula in the *ASHRAE Handbook* (2007):

$$E = 0.000144(p_w - p_r) \tag{5}$$

This formula is an adaptation of the Carrier (1918) formula based on Carrier's own tests on an unoccupied pool across which air was blown. It is recommended for air velocities from 0.05 to 0.15 m/s. Tests, for example by Smith et al. (1993) and Hanssen and Mathisen (1990), as well as CFD simulation by Li and Heiselberg (2005) show that velocity varies greatly from point to point in all three dimensions. It is not clear how the velocity for this formula is to be calculated. This formula is stated to be for occupied pools; the occupancy density is not specified. For unoccupied pools, the calculated value from Equation 1 is to be multiplied by 0.5.

Smith et al. (1993) performed tests on a public swimming pool. They gave the following correlation based on their own data:

$$E = 0.0000106(1.04 + 4.3N^*)(p_w - p_r) \tag{6}$$

They found that evaporation does not increase with an increase of occupancy $N^*$ beyond 0.16.

A widely used method is that by Verein Deutscher Ingenieure (VDI 1994). For occupied swimming pools,

$$E = 0.0000204(p_w - p_r) \tag{7}$$

The number of occupants is not stated. For unoccupied pools, the evaporation from Equation 7 is to be multiplied by 0.25.

Hens (2009) has given the following formula based on the measurements on a university swimming pool:

$$E = 0.0000409(1 + 8.46N^*)(p_w - p_r) \tag{8}$$

Shah (2003) gave two methods for calculating evaporation from occupied swimming pools. One is the following empirical correlation which was obtained by curve fitting to test data:

$$E = 0.023 - \frac{0.0000162}{U} + 0.041(p_w - p_r) \tag{9}$$

where $U$ is utilization defined as:

$$U = \frac{4.5N}{A} = 4.5N^* \tag{10}$$

The factor 4.5 is the area of the pool (in meters squared) per person according to German standard (Biasin and Krumme 1974). The pool is considered fully occupied when $U = 1$. Equation 5 was derived by curve fitting to data from three swimming pools. It is applicable to $U \geq 0.1$. For $U < 0.1$, linear interpolation is done between $E$ at $U = 0.1$ and $E_0$ by the Shah method (2012), Equations 3 and 4.

Shah (2003) also gave a calculation method taking into consideration the physical phenomena involved. His model is that the increase in evaporation is in direct proportion to the increase in water surface area caused by the occupants. The increase in area is because of waves, wet bodies of the swimmers, and the deck area wetted by occupants. Assumptions were made about the magnitude of these factors. It was assumed that the water temperature on the wet deck and on the occupant bodies is the same as on the pool's surface. The resulting formulas are:

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

$$E/E_0 = 1.3U + 1.2 \text{ for } 0.1 \leq U \leq 1 \tag{12}$$

$$E/E_0 = 2.5 \text{ for } U > 1 \tag{13}$$

This method showed fair agreement with available test data.

### Development of the New Correlation

The first approach tried was based on the generally held view that an increase in evaporation depends only on the number of occupants. Hence $E/E_0$ was plotted against occupancy $N^*$, as shown in Figure 1. The following equation was fitted to the data for $N^* \geq 0.1$.

$$E/E_0 = 2.33(1.43 - e^{(-11.25N^*)}) \tag{14}$$

This equation gave good agreement with most of the data, but some of the data had large deviations. Further study of the data indicated that for the same occupancy $N^*$, $E/E_0$ decreases with increasing $(\rho_r - \rho_w)$. By including this factor in data analysis, the following equation was developed:

For $N^* \geq 0.05$,

$$E/E_0 = 1.9 - 21(\rho_r - \rho_w) + 5.3N^* \tag{15}$$

For $N^* < 0.05$, perform linear interpolation between $E/E_0$ at $N^* = 0.05$ and $E/E_0 = 1$ at $N^* = 0$. For

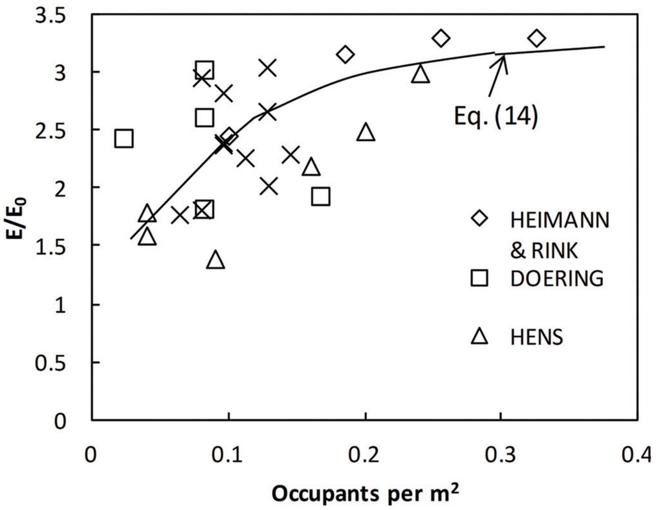

***Figure 1*** *Increase in evaporation with occupancy shown by data of various researchers and Equation 14, the first correlation tried during this research.*

$(\rho_r - \rho_w) < 0$, use $(\rho_r - \rho_w) = 0$. This formula gave significantly better agreement with the data than Equation 14.

The reason for this inverse dependence on air density difference is explained as follows. Larger air density differences occur when water temperature is higher than the air temperature. When water spills on the deck, it quickly cools down to air temperature, as was pointed out by Smith et al. (1993). Hence, the density difference for the deck area is much smaller than for the pool area. Therefore, increase in evaporation with occupancy is much lower at high values of $(\rho_r - \rho_w)$. On the other hand, if the pool water temperature is the same as the air temperature, the density difference over the deck area will be about the same as for the pool area. The increase in evaporation with increasing occupancy will then be in proportion to the wetted deck area. The situation regarding the evaporation from wet bodies of occupants will be similar.

Thus, Equation 15 is consistent with the physical phenomena and gives better agreement with data than Equation 14, as is shown later. Equation 15 is therefore chosen as the recommended formula and is henceforth called the present correlation.

## Test Data for Evaporation in Occupied Swimming Pools

Intense efforts were made to collect test data for occupied swimming pools. Analyzable data were found from only four studies. The range of their data is listed in Table 1. Tests are also reported by Hyldgaard (1990), Hens (2009), and Smith et al. (1993). However, the data given in those publications do not have sufficient details to be analyzed and the detailed data could not be found despite much effort.

## Comparison of Test Data with Various Formulas

The data listed in Table 1 was compared with the new correlations (Equations 14 and 15), as well as with other published correlations for occupied pools mentioned earlier (Equations 3 to 13). A few data points from Biasin and Krumme (1974) showed evaporation less than that from unoccupied pools and gave large deviations from all formulas; those data were not considered. All other data were analyzed. The results of data analysis are shown in Tables 2 and 3. In these tables, deviation $\delta$ is defined as

$$\delta = (\text{prediction} - \text{measurement}) / \text{measurement} \qquad (16)$$

The mean deviation of each data set is defined as

$$\text{Mean deviation} = \frac{\sum(\delta)}{M} \qquad (17)$$

where $M$ is the number of data points in the set. Mean absolute deviation is defined as

$$\text{Mean absolute deviation} = \frac{\sum(\text{absolute value of } \delta)}{M} \qquad (18)$$

**Table 1. Range of Test Data Analyzed**

| Source | Pool Area, m$^2$ (ft$^2$) | Persons Per m$^2$ (per ft$^2$) | Air Temperature, °C (°F) | RH, % | Water Temperature, °C (°F) | $(\rho_r - \rho_w)$ kg/m$^3$ (lb/ft$^3$) | $(p_w - p_r)$ Pa (in. Hg) |
|---|---|---|---|---|---|---|---|
| Doering<br>(1979) | 425<br>(4575) | 0.082 (0.008)<br>0.167 (0.017) | 27.5 (81.5)<br>29.0 (84.2) | 33<br>41 | 25.0 (77) | 0.0024 (0.00015)<br>0.0153 (0.00096) | 1526 (0.45)<br>2141 (0.63) |
| Biasin and Krumme<br>(1974) | 64<br>(689) | 0.016 (0.0015)<br>0.325 (0.03) | 26.0 (78.8)<br>30.0 (86.0) | 46<br>72 | 26.0 (78.8)<br>30.0 (86.0) | –0.0013 (–8x10$^{-5}$)<br>0.0313 (0.0019) | 1067 (0.31)<br>2087(0.62) |
| Heimann and Rink<br>(1970) | 200<br>(2153) | 0.10 (0.0093)<br>0.325 (0.039) | 31.0 (87.8) | 54<br>55 | 28.5 (83.3) | 0.007 (0.00044) | 1422 (0.42) |
| Hanssen and Mathisen<br>(1990) | 72<br>(774) | 0.028 (0.037)<br>0.486 (0.045) | 30.0 (86.0) | 60<br>65 | 32.0 (89.6) | 0.0312 (0.00195)<br>0.0421 (0.0026) | 2084 (0.62)<br>2377 (0.70) |

**Table 2. Deviations of Various Formulas with Test Data**

| Source | Evaluated Formulas | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ASHRAE (2007) | VDI (1994) | Smith et al. (1993) | Hens (2009) | Shah (2003) Empirical | Shah (2003) Phenomenological | New Equation 14 | Present Equation 15 |
| Doering (1979) | 15.3 | 60.2 | 20.6 | –42.8 | –0.4 | –24.3 | 0.9 | –7.0 |
| | 17.2 | 60.2 | 21.5 | 42.8 | 6.0 | 29.1 | 29.9 | 23.9 |
| Hanssen and Mathisen (1990) | –34.2 | –8.6 | –28.6 | –51.0 | –49.0 | –27.0 | –4.8 | –18.7 |
| | 34.2 | 26.4 | 28.6 | 51.0 | 49.0 | 27.0 | 7.2 | 20.1 |
| Heimann and Rink (1970) | –4.5 | 32.7 | 16.6 | –25.4 | –8.1 | –26.1 | –0.9 | –5.5 |
| | 13.0 | 32.7 | 16.6 | 25.4 | 14.3 | 26.1 | 3.2 | 8.1 |
| Biasin and Krumme (1974) | 39.9 | 94.3 | 36.2 | –38.8 | 32.7 | –5.1 | 24.0 | 6.8 |
| | 44.4 | 94.3 | 37.8 | 38.8 | 36.2 | 23.6 | 27.7 | 17.9 |
| All data | 18.3 | 64.3 | 20.7 | –39.7 | 8.9 | –14.4 | 12.4 | –1.1 |
| | 34.3 | 69.9 | 31.0 | 39.7 | 30.6 | 25.3 | 21.5 | 18.0 |

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

**Table 3. Number of Data Points with Deviations Exceeding 30% for Various Formulas.**

| Source | Total Data Points | Evaluated Formulas | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ASHRAE (2007) | VDI (1994) | Smith et al. (1993) | Hens (2009) | Shah Empirical (2003) | Shah Phenomenological (2003) | New Equation 14 | Present Equation 15 |
| Doering (1979) | 5 | 1 | 5 | 2 | 2 | 0 | 3 | 3 | 1 |
| Hanssen and Mathisen (1990) | 5 | 3 | 4 | 3 | 4 | 4 | 2 | 0 | 1 |
| Heimann and Rink (1970) | 4 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 |
| Biasin and Krumme (1974) | 17 | 6 | 15 | 7 | 15 | 5 | 4 | 6 | 2 |
| All data | 31 | 10 | 25 | 12 | 23 | 9 | 9 | 9 | 4 |
| Percent of Data with Deviation >30% | | 32.2 | 80.6 | 38.7 | 74.2 | 29.0 | 29.0 | 29.0 | 12.9 |
| Percent data within ±30% | | 77.8 | 19.4 | 61.3 | 33.8 | 71.0 | 71.0 | 71.0 | 87.1 |

Table 2 lists the deviations while Table 3 lists the number of data points for which deviation exceeds ±30%. Figures 2 and 3 show the comparison of test data with the present correlation as well as those of Hens (2009) and Smith et al. (1993). It is seen that the present correlation gives significantly better agreement with data.

## DISCUSSION

### Accuracy

In Table 2, it is seen that the present correlation, Equation 15 has the least mean absolute deviation at 18%. The next best is Equation 14 at 21.5%. The Shah phenomenological formula (2003) has a mean absolute deviation of

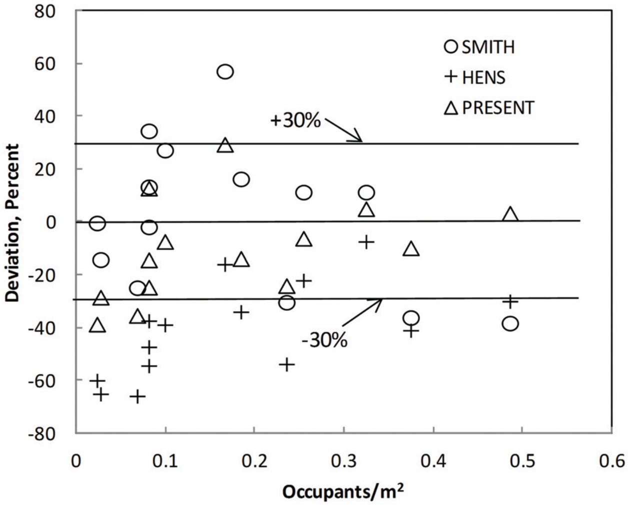

***Figure 2*** *Comparison of test data with the present correlation and those of Hens (2009) and Smith et al. (1993). Test data of Heimann and Rink (1970), Hanssen and Mathisen (1990), and Doering (1979).*

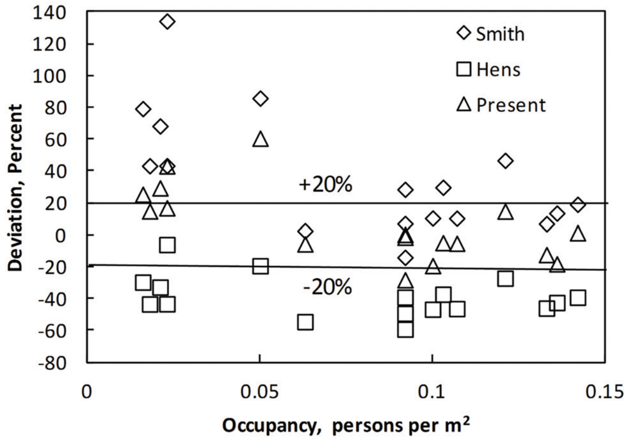

***Figure 3*** *Comparison of test data of Biasin and Krumme (1974) with the present correlation and those of Hens (2009) and Smith et al. (1993).*

25.1%. All the other formulas have poor performances, mean absolute deviations exceeding 30%. In Table 3, it is seen that 87% of the data analyzed are predicted within ±30% by the present correlation, Equation 15. The next best are Equation 14, Shah empirical correlation, and Shah phenomenological correlation, each predicting 71% of data within ±30%. Thus, the present correlation is clearly considerably superior to other correlations.

While the agreement of the present correlation with the available data is good, the data is from only four sources. Verification with more data is desirable. It is hoped that more data will be published.

## Effect of Occupancy

Figure 4 shows the effect of occupancy according to the correlations of Hens (2009) and Smith et al. (1993). Also shown are the predictions of the present correlation at density differences $\Delta\rho$ of 0 and 0.05 kg/m$^3$ (0.0031 lb/ft$^3$). It is seen that the correlations of Smith et al. and Hens differ considerably. The present correlation at $\Delta\rho = 0.05$ is fairly close to the Smith et al. correlation in the range of their data. The Hens correlation is fairly close to the present correlation at $\Delta\rho = 0$. This behavior suggests that the difference in the behavior of the Hens and Smith et al. correlations may be due to differences in density differences during their tests.

## CONCLUDING REMARKS

1. A new correlation has been presented for the effect of occupancy on the rate of evaporation from swimming pools. It shows good agreement with available test data, the mean absolute deviation being 18%.
2. An important feature of the new correlation is that it takes into account the effect of density difference between room air and air at pool surface besides the effect of the number of occupants on evaporation rate. Earlier correlations had not considered the effect of density difference and this seems to be the reason for the differences in their trends for occupancy.
3. Several other published correlations were also evaluated against the same data. Their performance was far inferior, mean absolute deviations varying from 25% to 70%.
4. The new correlation will help in correct sizing of HVAC systems and in making accurate energy consumption estimates for swimming pools.
5. The new formula presented here has been validated with all published test data but these are from only four independent studies. Comparison with more data is desirable. It is therefore suggested that more tests be done on occupied pools to study the effects of varying occupancy and air density differences. Availability of test data from earlier studies, such as Smith et al. (1993), will also be very helpful.

## NOMENCLATURE

All equations in the foregoing main text use the SI units listed below. The formulas with I-P units are given in the Appendix.

$A$ = area of pool surface, m$^2$
$E$ = rate of evaporation from occupied pools, kg/m$^2$h
$E_0$ = rate of evaporation from unoccupied pools, kg/m$^2$h
$N$ = number of persons in the pool
$N^*$ = $N/A$

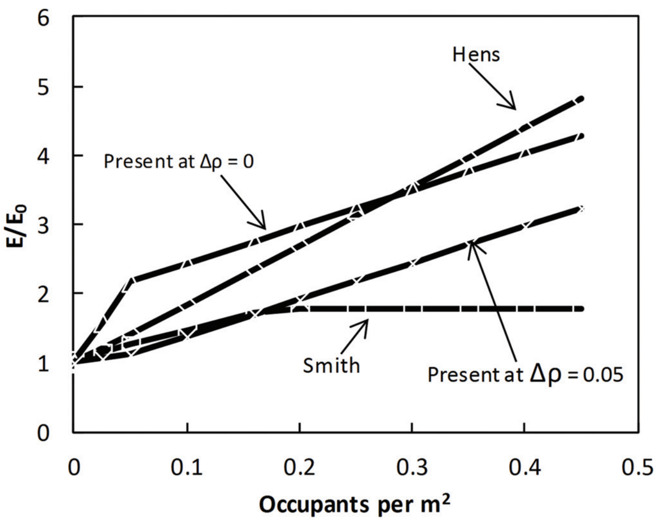

*Figure 4* *Effect of occupancy on evaporation according to the present correlation and those of Hens (2009) and Smith et al. (1993).*

$p$ = partial pressure of water vapor in air, Pascals

$U$ = utilization factor = $4.5N^*$

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

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

$\Delta\rho$ = $(\rho_r - \rho_w)$, kg/m$^3$

### Subscripts

$w$ = saturated at water surface temperature

$r$ = at room temperature and humidity

## APPENDIX

The main paper uses the SI units listed in the Nomenclature section. This appendix is in I-P units.

The following new formula was developed for evaporation from occupied pools.

$$E/E_0 = 1.9 - 336(\rho_r - \rho_w) + 57N/A \tag{A-1}$$

Equation 1 applies to $(N/A) \geq 0.0046$ persons/ft$^2$. For $N = 0$, $E/E_0$. For $(N/A) < 0.0046$, interpolate between $E/E_0$ at $(N/A) = 0.0046$ and 1. For $(\rho_r - \rho_w) < 0$, use $(\rho_r - \rho_w) = 0$.

$E_0$ is calculated by Shah's published method (2012). According to it, evaporation rate is the larger of those given by the following two equations:

$$E_0 = 290\rho_w(\rho_r - \rho_w)^{1/3}(W_w - W_r) \tag{A-2}$$

$$E_0 = 0.0346(p_w - p_r) \tag{A-3}$$

In the above equations, $A$ is in ft$^2$, $E$ is in lb/hr·ft$^2$, $p$ is in inches of mercury, and $\rho$ is in lb/ft$^3$.

## REFERENCES

ASHRAE. 2007. *ASHRAE Handbook—HVAC Applications*. Atlanta: ASHRAE.

Biasin, K. and W. Krumme. 1974. Die Wasserverdunstung in einem Innenschwimmbad. *Electrowaerme International* 32(A3):A115-A129.

Carrier, W.H. 1918. The temperature of evaporation, *ASHVE Trans*., 24:25–50.

Doering, E. 1979. Zur Auslegung von Luftungsanlagen fur Hallenschwimmbaeder, *HLH* 30(6):211–6.

Hanssen, S.A., and H.M. Mathisen. 1990 Evaporation from swimming pools, Roomvent 90: 2nd International Conference, June 13–15, Oslo, Norway.

Heimann and Rink (1970), quoted in Biasin and Krumme (1974). Die Wasserverdunstung in einem Innenschwimmbad. Electrowaerme International.

Hens, H. 2009. Indoor climate and building envelope performance in indoor swimming pools. *Energy Efficiency and New Approaches: Proceedings of the Fourth International Building Physics Conference*, June 15–18, Istanbul, Turkey. 543–52.

Hyldgaard, C.E. 1990. Water evaporation in swimming baths. *Roomvent '90, International Conference on Engineering Aero- and Thermodynamics of Ventilated Rooms, Oslo, June*.

Li, Z. and P. Heiselberg. 2005. CFD Simulations for Water Evaporation and Airflow Movement in swimming Baths. *Report Department of Building Technology and Structural Engineering*, Aalborg University, Denmark.

Smith, C.C., R. Jones, R. and Lof, G. 1993. Energy requirements and potential savings for heated indoor swimming pools, *ASHRAE Transactions* 99(2): 864–74.

Shah, M.M. 2012. Calculation of evaporation from indoor swimming pools: further development of formulas. *ASHRAE Transactions* 118(2).

Shah, M.M. 2003. Prediction of evaporation from occupied indoor swimming pools. *Energy and Buildings* 35:707–13.

VDI, 1994. Wärme, Raumlufttechnik, Wasserer- und –entsorgung in Hallen und Freibädern, Verein Deutscher Ingenieure 2089.