Measurement and Analysis of Evaporation in Indoor Swimming Pools: Comparison with the ASHRAE's Activity Factor

Ole Øiene Smedegård[1,2*], Bjørn Aas[2], Jørn Stene[1], Laurent Georges[3]
[1]COWI AS, Trondheim, Norway
[2]SIAT NTNU - Centre for Sport Facilities and Technology, Norwegian University of Science and Technology, Department for Civil and Transport Engineering, Trondheim, Norway
[3]Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
** corresponding author: oosm@cowi.com*

Abstract

The evaporation rate from the swimming pool is a main parameter influencing the energy use in swimming facilities. Quantifying this phenomenon is crucial when modelling the facility in Building Performance Simulation. This study investigates the accuracy of ASHRAE equation using field measurements. This equation is widely used and implemented in BPS tools, such as the pool model in IDA ICE. The investigated dataset was based on two different indoor swimming pool facilities in Norway. It includes in total 75 swimming lessons (i.e., occupied pool) and 477 hours of unoccupied operation. While ASHRAE recommend 1.0/0.5 for occupied and unoccupied pools, respectively, the average activity factor was found to be 0.7 and 0.8 for the investigated occupied pools, with a maximum at 1.1. Moreover, the activity factor was between 0.50 and 0.57 for unoccupied pools.

Introduction

Precise calculation of the evaporation rate is essential when planning and optimizing the indoor environmental and energy system in swimming facilities. Evaporation is very energy-intensive and affects both the water side and the air side of the boundary layer along the water surface. On the water side, the evaporation cools the pool water while on the air side, the evaporation contributes to high indoor relative humidity which must be controlled to ensure a safe indoor climate for both the building and the users. Building performance simulation (BPS) tools approaches the task of calculation of the evaporation rate in different manners with different equations.

Over the last century, a number of scientific studies regarding the prediction of the evaporation rate have been published. The results differs considerably (Shah 2014) and there has not been found any consensus in this field (Smedegård et al. 2021). The various studies have been carried out using both laboratory experiments and on-site experiments.

One of the most commonly used correlations was published by Carrier in 1918 (Carrier 1918). This correlation was developed by measurement data from small-scale laboratory experiments. The equation, which is based on Dalton description (Dalton 1802), has a simple structure and is recommended by ASHRAE's handbooks (ASHRAE 2015). Despite the fact that the setup only included experiments with forced convection, the equation is widely used for cases with air speed down to 0 m/s. ASHRAE has simplified the equation by reducing the air speed variable to zero. The equation is recommended for estimating the evaporation rate for occupied pools. ASHRAE has also distributed recommendations of activity factors based on the type of pool. For cases with an unoccupied pool, it's recommended to multiply the results by 0.5. No reference to this recommendation is found in the literature. This equation is widely used and e.g. implemented in the BPS tool IDA ICE's Pools extension (EQUA Simulation AB 2022).

Through the 1990's, Smith et al. (Smith et al. 1993, 1994; Smith et al. 1998) investigated the accuracy of Carrier's equation for both indoor and outdoor pools, occupied and unoccupied. Through their research, they found that the equation underpredicted the evaporation rate when the pool was occupied and overpredicted it when the pool was unoccupied.

In parallel with Smith et al., Shah published several articles in which he presented an algorithm for calculating the evaporation rate for indoor occupied and unoccupied pools (Shah 1992, 2002, 2003, 2008, 2012a, 2013, 2014). His algorithm includes equations that were developed from both a theoretical and empirical basis. He validated his method using all available measurement data from other test studies and proved that the method produced the most reliable results. Similar to Smith et al., Shah also implemented a variable describing the use of the swimming pool. While Smith et al. recommended the use of a correction factor of 0.76 and 1.26 for unoccupied and occupied pools, respectively, Shah recommended the use of a variable identifying the number of people in the pool, where an increasing number of bathers increases the evaporation rate. Hanssen and Mathisen (1990) applied the same variable, the number of bathers, in their study. However, one of the findings was that the evaporation rate was observed as a step function, where the number of bathers did not influence the evaporation rate as much as the operation of the pool itself (meaning occupied or unoccupied). Hanssen and Mathisen based their research on full-scale experiments, with school children as bathers. None of the mentioned studies quantified the activity level of the bathers.

Table 1 Overview of the applied methods for identifying evaporation rate in the literature.

Authors	Year	Title	Method	Comment
Hanssen and Mathisen (Hanssen. and Mathisen. 1990)	1990	"Evaporation from swimming pools"	Moist mass balance (air)	Occupied/ Unoccupied
Smith et al. (Smith et al. 1993)	1993	"Energy requirements and potential savings for heated indoor swimming pools"	Water mass balance	Unoccupied
Smith et al. (Smith et al. 1998)	1998	"Rates of evaporation from swimming pools in active use"	Energy balance for the pool circuit	Occupied
Shah, M. M. (Shah 2002)	2002	"Evaluation of available correlations for rate of evaporation from undisturbed water pools to quiet air"	Moist mass balance (air), water mass balance and air flow	Occupied/ Unoccupied
Lu, T., et al. (Lu et al. 2014)	2014	"Prediction of water evaporation rate for indoor swimming hall using neural networks"	Moist mass balance (air)	Occupied/ Unoccupied
Ciuman, P. and B. Lipska (Ciuman and Lipska 2018)	2018	"Experimental validation of the numerical model of air, heat and moisture flow in an indoor swimming pool"	Air state in the room, comparison with CFD-model calculations	Unoccupied

Based on these studies and their use of the activity factor to calculate the evaporation rate, this paper investigates the activity factor in the ASHRAE equation which

$$\dot{m}_{evap} = 4 \cdot 10^{-5} \cdot A_{pool} \cdot F_{act} \cdot (p_w - p_a) \qquad (1)$$

describes the use of the pool, i.e. the number of bathers, their activity level and how these can be represented by an activity factor. This represents a crucial input variable when estimating the performance of swimming pools in BPS tools.

Method

The paper investigates full-scale measurements of the evaporation rate for swimming pools. The general approach of this study is described by three stages.

1. Measure the evaporation rate and quantify the usage of the pool, both number of users and their respective activity level.
2. Calculate the corresponding activity factor by combining the measured evaporation rate with the ASHRE equation
3. Compare calculated activity factor with recommended activity factor given by ASHRAE (2015) with the aim to validate the selection of this factor.

The ASHRAE equation is given as Equation 1. $\dot{m}_{evap}$ represent the evaporation rate [kg/s], A_{pool} is the area of pool surface [m²], p_w is the saturation vapor pressure taken at surface water temperature [kPa], p_a is the saturation pressure at room air dew point [kPa] and F_{act} is the activity factor [-].

The evaporation rate was experimentally investigated in two separate swimming facilities, with similar layout and user groups. The evaporation and usage data were collected during the period of January to March 2020, at the multipurpose center at Jøa and Dalgård school in Trondheim, both in Norway.

Measuring the evaporation rate is not straightforward as it cannot be measured directly. In the literature, several methods for measuring evaporation have been applied. These can be described by [1] the energy balance for water circuit, [2] the mass balance for water circuit and [3] the moist mass balance for swimming hall. Table 1 shows an overview of methods that have been used in some of the available research articles within the topic. Our study was performed by applying the moisture mass balance for the swimming hall. The equation is given in Equation (2) while Figure 1 shows a schematic illustration of the mass balance. m_{room} is the moist content in the swimming hall room in [kg], $\dot{m}_{sup}$ is the supplied moist mass flow rate by supply air [kg/s], $\dot{m}_{evap}$

is the supplied moist mass flow rate due to evaporation from the water surface in [kg/s], $\dot{m}_{inf}$ is the supplied moist mass flow rate by due to infiltration in [kg/s] and $\dot{m}_{ext}$ is the extracted moist mass flow rate by the extract air flow in [kg/s].

$$\frac{dm_{room}}{dt} = \dot{m}_{sup} + \dot{m}_{evap} + \dot{m}_{inf} - \dot{m}_{ext} \qquad (2)$$

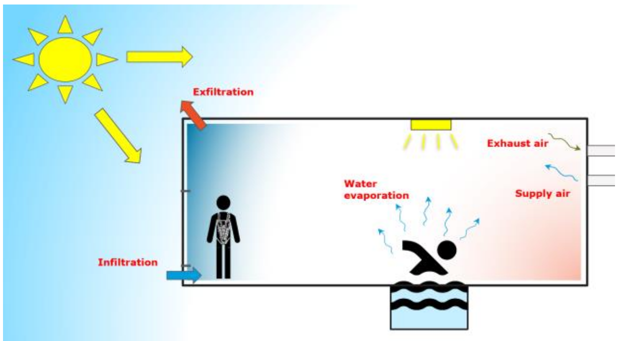

Figure 1 Schematic illustration of the key components affecting in the mass balance in the hall.

The experimental campaign comprised data of in total 75 swimming sessions and 477 hours with the pool unoccupied. The experimental data from the swimming facility at Jøa included 31 swimming sessions and 385 hours with the pool unoccupied, while the swimming facility at Dalgård covered 44 swimming sessions and 92 hours of unoccupied operation. Both swimming pools have the same size, i.e., 100 m^2 and 12.5 m long, and are used for educational purposes during school hours, and by individuals and organizations otherwise. Table 2 shows the pool water temperature, the dry bulb temperature for the room air and the nominal extract air volume flow rate for the facilities observed during the period of data collection. Figure 2 shows the swimming pools of Jøa and Dalgård.

Table 2 Pool water temperature, room air dry-bulb temperature and extract air volume flow rate for Dalgård and Jøa.

	Dalgård	**Jøa**
Pool water temperature	Avg - 33.0 °C Min/max 32.5/33.5 SD - 0.3	Avg - 31.1 °C Min/max 30.2/31.4 SD - 0.17
Room temperature	32.0 °C Min/Max 31.6/32.3 SD - 0.13	31.5 °C Min/max - 31.4/31.7 SD - 0.05
Air flow (day/night)	6500/6500 m^3/h	8200/6600 m^3/h

Results

Figure 3, Figure 4 and Figure 5 illustrate the results from the campaigns at Dalgård and Jøa. The evaporation rate data for occupied pool was averaged for each swimming session. The evaporation rate data when the pools were unoccupied, was averaged for each hour.

For the case of Dalgård, the activity level of the users was observed for each swimming session. This range is presented in Figure 7 where the activity level is averaged for each session.

The activity level was defined on a scale from 1 to 3, in steps of 0.5, where 1 represents recreational easy swimming and 3 is high activity with splashing and waves. It needs to be emphasized that the registered activity levels did not correspond to ASHRAE's activity factor since they didn't include the number of bathers present in the pool.

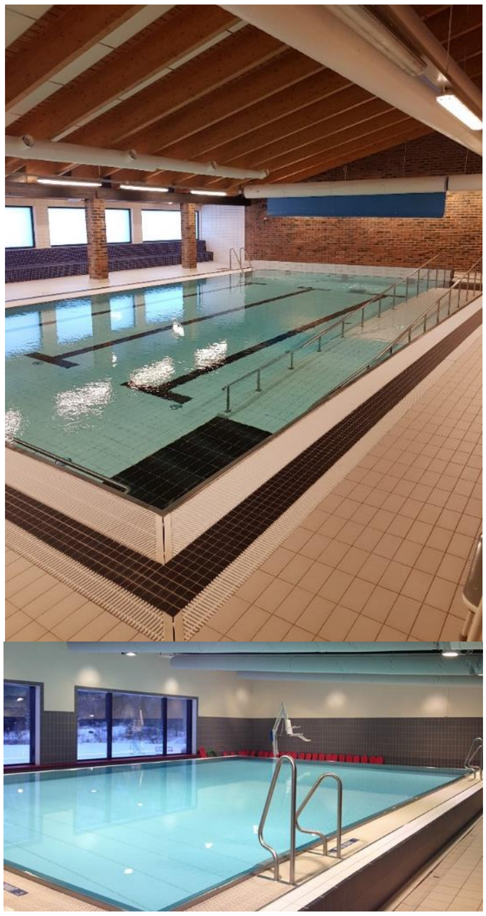

Figure 2 The swimming pool at Dalgård (upper) and Jøa (lower).

Table 3 summarizes the recommended activity factors provided by the ASHRAE handbook (ASHRAE 2015). The increased activity factor, from unoccupied to occupied pools, reflects the increased contact area between air and water due to waves, ripples and mist, which also increase with the number of occupants and the activity level. This implies an increase of the "active" pool area (Shah 2012b).

For the case of unoccupied pools, ASHRAE (2015) recommends a activity factor of 0.5, ref.

Table 3. This level is also reflected in the results of the experimental campaigns at Jøa and Dalgård, which were represented by an averaged activity factor of 0.5 and 0.57, respectively. The results regarding the evaporation rate

for unoccupied pools is shown in Figure 3. The difference in the activity factor for these swimming pools addresses several explanatory variables. Firstly, the ventilation concept, i.e. the air distribution, differ for these two swimming facilities, as shown in Figure 2.

Table 3 Recommended activity factors given in the ASHRAE handbook.

Type of Pool	Activity Factor F_a
Baseline (pool unoccupied)	0.5
Residential pool	0.5
Condominium	0.65
Therapy	0.65
Hotel	0.8
Public, schools	1.0
Whirlpools, spas	1.0
Wave pools, water slides	1.5

At Dalgård, the air is supplied by air-nozzles, while at Jøa it is based on diffuse air supply by textile ducts beneath the ceiling. In addition, one of the extract grills at Dalgård is placed close to the floor, and also to the pool surface. These differences in ventilation design imply a possible higher air speed close to the water surface at Dalgård, which increases the evaporation rate. Another possible explanatory variable is the difference in water and air temperature. Even though this is taken into account in the respective water vapor saturation pressures in Equation 1, this implies that the ASHRAE equation does not takes this into account in a proper way. However, considering the large difference in absolute evaporation rates between these facilities, the calculated activity factors for unoccupied pools was found to agree with the recommended value provided by ASHRAE. The absolute evaporation rate for the two swimming facilities was characterized by an average value of 24.3 kg/h for Dalgård and 14.3 kg/h for Jøa.

For the occupied pool experiments the calculated activity factors are given in Figure 4. The range of the calculated factors indicates a wide variation in swimming session types for both swimming facilities. The evaporation rate at Dalgård has an average value of 33.5 kg/h, with a maximum of 45.9 kg/h and a minimum of 19.2 kg/h. The corresponding numbers at Jøa is 20.4 kg/h in average for each session, a maximum of 29.1 kg/h and a minimum of 12.9 kg/h. As mentioned, the boundary conditions are different so the absolute level of these numbers should not be compared without considering these differences.

Regarding the activity factors for occupied pools, Dalgård is characterized by an average of approx. 0.8, ranging from 0.5 to 1.1, while Jøa is represented with an average of 0.7, ranging from 0.4 to 1.1. These key numbers show that the pools are normally below the provided recommendation from ASHRAE, which recommends 1.0 for occupied school pools. However, considering the numbers of occupants represented in the dataset of the swimming sessions, it seems to be below what was considered as design conditions for such pools.

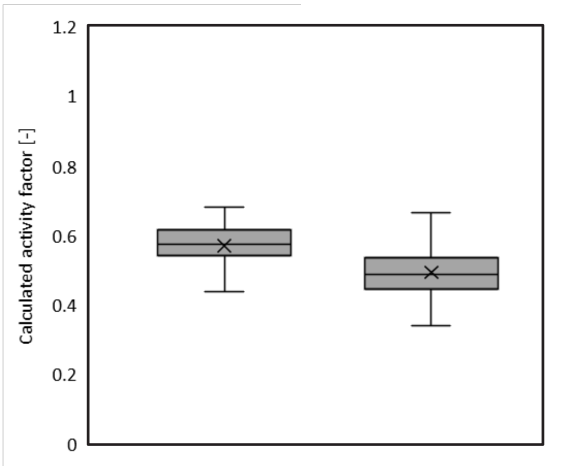

Figure 3 Box plot presenting the calculated activity factor based on the unoccupied pool measurements at Dalgård (left) and Jøa (right).

Pools of this depth, as Jøa and Dalgård, are normally designed for a user intensity of 2,7 m^2/swimmer (Verein Deutscher Ingenieure 2010; Norsk Bassengbad Teknisk forening 2000). This gives a design load of 37 bathers. Compared to the collected user intensity in our dataset, the use of these pools is neither at this level, neither in average or maximum. Figure 5 show the user intensity where Dalgård is represented with an average load of 11 bathers, ranging from 3 to 22 bathers/session. Jøa is represented with an average load of 7 bathers, ranging from 1 to 20 bathers.

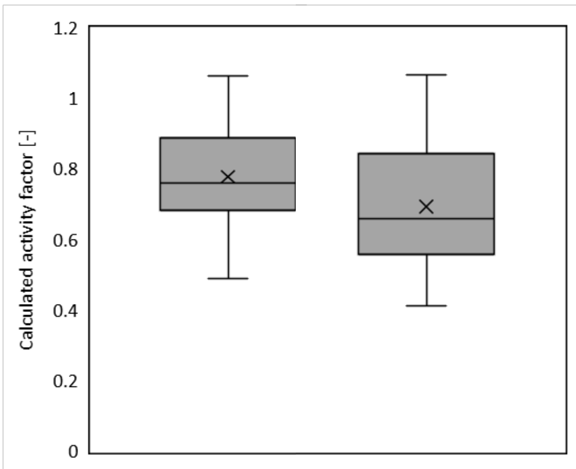

Figure 4 Box plot presenting the calculated activity factor based on the measurements and observations for occupied pool for Dalgård (left) and Jøa (right).

The difference in user intensity between these facilities is also found in the calculated activity factors. Both facilities are identified with a maximum calculated activity factor of approx. 1.1. as well as a maximum user intensity of approx. 20 swimmers (20 for Jøa and 22 for Dalgård). This corresponds well and implies that an activity factor of 1.1 represents the design condition. The difference in the average activity factor is found to differ, which is expected due to the difference in average user intensity. Also, the minimum calculated activity factor is found to differ between these facilities, even in a minor manner. In addition to the lower minimum user intensity at Jøa, the beforementioned difference in the ventilation concept may be the main cause influences for this difference.

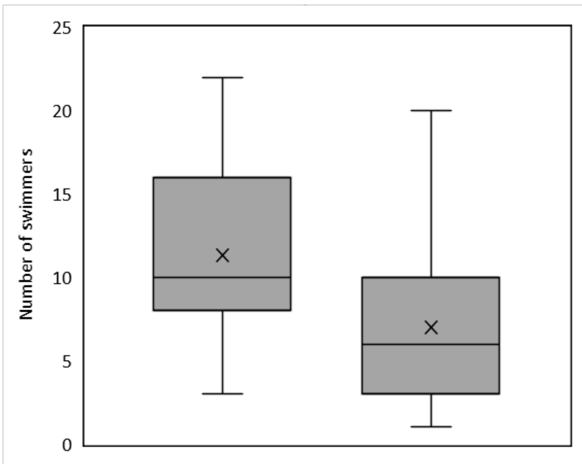

Figure 5 Box plots presenting the number of swimmers present in each session for Dalgård (left) and Jøa (right).

While it was observed that the number of bathers had a large influence on the evaporation rate, it does not explain it completely. Figure 6 shows the evaporation rate plotted against number of bathers, with Jøa in black circles and Dalgård in red circles.

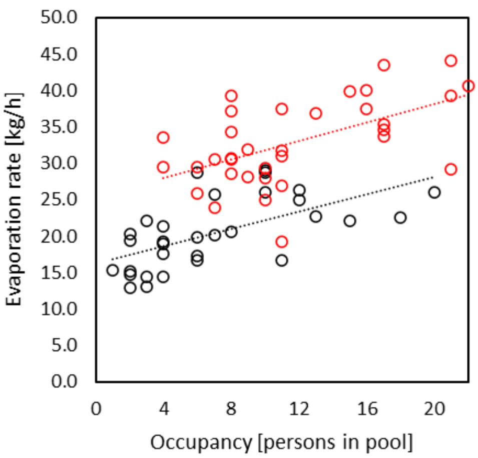

Figure 6 Scatter plot of the evaporation rate plotted against number of bathers: Black circles - Jøa; Red circles - Dalgård.

Beside the consistent difference in the evaporation rate for all levels of occupancy it was seen a spread in the average evaporation rate for the same number of occupants. This is obviously due to the user influence and the type of swimming/bathing sessions that were carried out. High activity level includes heavy waves and splashing which result in an increased evaporation rate. For Dalgård this variable was observed, quantified, and logged. Figure 7 shows the spread of the activity level among the same sizes of groups. It was seen that the activity level tended to increase with the size of the group. The maximum calculated activity factor of 1.1 represents the largest group of bathers with high activity level, which may be considered as the design conditions for this kind of swimming facilities.

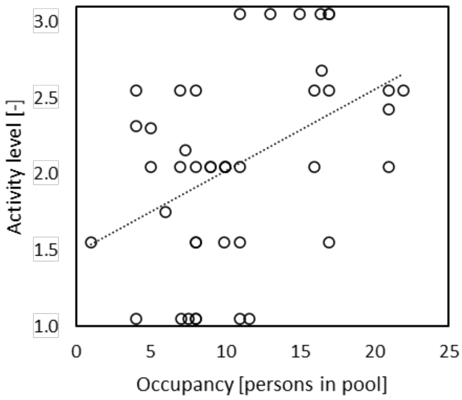

Figure 7 Dalgård – The observed activity level for each of the swimming sessions plotted against the number of bathers for the session.

Conclusion

When simulating the performance of swimming facilities in BPS tools, the calculation of the evaporation rate is crucial for the results, both with respect to indoor environment and to annual energy consumption. Despite several equations available in literature no consensus regarding method have been observed. In this study, measurements and observations regarding the use of the pool were collected to evaluate the evaporation rate. In total, data from 75 swimming sessions and 477 hours of unoccupied operation in two different school pools in Norway was analyzed. By combining the experimental results with the well-known and widely used ASHRAE equation, the study evaluated the activity factor used in this equation. During the design phase of a swimming pool, this variable is normally defined by the expected operating mode of the swimming facility, i.e. periods when the swimming facility is open for the public. However, this may give considerable inaccuracy of the energy consumption of the HVAC installation. This study has evaluated the activity factor as a function of the real operating conditions. The ASHRAE handbooks recommends an activity factor of 1.0 when the pool is occupied and 0.5 when unoccupied.

- Regarding the latter, our study is in good agreement with this recommended level. The average activity levels were found to be 0.5 and 0.57 for the two swimming facilities. Based on this it is recommended to use 0.5 for unoccupied pools.
- Regarding the activity factor for occupied pools, it was found that using the ASHRAE recommendation of 1.0 will probably overpredict the average

evaporation rate for most swimming facilities. The average activity factor when the pools were occupied were 0.7 and 0.8 in this study. When predicting annual energy consumption in BPS tools the activity factor should be carefully evaluated and the average level should be reduced from the recommended level in ASHRAE, but not below 0.7, which represents a swimming facility with diffuse ventilation system and reduced circulated air flow when the pool is not occupied.

- In design, rating condition is defined when the pools are considered fully occupied and with high activity level. Rating conditions represent extreme condition typically when sizing equipment or evaluating indoor environment. For this purpose, it was found that the ASHRAE's recommended activity factor is too low. Based on the findings in this study it is recommended to increase the recommended activity factor in ASHARE by 10 %, to 1.1, for rating condition.

Acknowledgement

This work is a part of a doctoral project entitled "*Optimizing Energy and Climate Systems in Buildings with Swimming Facilities*," which is carried out as a cooperation project between the Centre for Sport Facilities and Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, and the engineering company COWI AS. The project is funded by COWI AS, The Research Council of Norway and COWIFonden.

References

ASHRAE (2015). Applications Handbook. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta GA.

Carrier, W. H. (1918). The temperature of evaporation. *ASHVE Transactions, 24*, 25-50.

Ciuman, P., & Lipska, B. (2018). Experimental validation of the numerical model of air, heat and moisture flow in an indoor swimming pool. [Article]. *Building and Environment, 145*, 1-13, doi:10.1016/j.buildenv.2018.09.009.

Dalton, J. (1802). Experimental essays on the constitution of mixed gases. *Manchester Literary and Philosophical Society Memo, 5*, 535-602.

EQUA Simulation AB (2022). Building Performance - Simulation Software EQUA - Ice rink and pools extension. https://www.equa.se/en/ida-ice/extensions/ice-rinks-and-pools.

Hanssen., S. O., & Mathisen., H. M. Evaporation from swimming pools. In *Roomvent, Norway,Oslo 13-15 June 1990*

Lu, T., Lü, X., & Viljanen, M. (2014). Prediction of water evaporation rate for indoor swimming hall using neural networks. *Energy and Buildings, 81*, 268-280, doi:10.1016/j.enbuild.2014.06.027.

Norsk Bassengbad Teknisk forening (2000). Retningslinjer for vannbehandling i offentlige bassengbad.

Shah, M. M. (1992). Calculating evaporation from pools and tanks. . *Heating, Piping, Air Conditioning, 64*(4), 69-71.

Shah, M. M. (2002). Evaluation of available correlations for rate of evaporation from undisturbed water pools to quiet air. *HVAC&R Research, 8*(1), 125, doi:10.1080/10789669.2002.10391292.

Shah, M. M. (2003). Prediction of evaporation from occupied indoor swimming pools. *Energy and Buildings, 35*(7), 707-713, doi:10.1016/S0378-7788(02)00211-6.

Shah, M. M. (2008). Analytical formulas for calculating water evaporation from pools. *ASHRAE Transactions, 114*(2), 610-618.

Shah, M. M. (2012a). Calculation of evaporation from indoor swimming pools: further development of formulas. *ASHRAE Transactions, 118*(2), 460-466.

Shah, M. M. (2012b). Improved method for calculating evaporation from indoor water pools. *Energy and Buildings, 49*, 306-309, doi:10.1016/j.enbuild.2012.02.026.

Shah, M. M. (2013). New correlation for prediction of evaporation from occupied swimming pools.(Report). *ASHRAE Transactions, 119*(2), 450-455.

Shah, M. M. (2014). Methods for Calculation of Evaporation from Swimming Pools and Other Water Surfaces. *ASHRAE Transactions, 120*, 3-17.

Smedegård, O. Ø., Aas, B., Stene, J., Georges, L., & Carlucci, S. (2021). Systematic and data-driven literature review of the energy and indoor environmental performance of swimming facilities. *Energy Efficiency, 14*(7), 74, doi:10.1007/s12053-021-09985-6.

Smith, C. C., Jones, R. W., & Lof, G. O. G. (1993). *Energy requirements and potential savings for heated indoor swimming pools.* Paper presented at the Proceedings of the 1993 Annual Meeting of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, Denver, CO, USA, 23-27 January 1993

Smith, C. C., Jones, R. W., & Lof, G. O. G. (1994). Measurement and analysis of evaporation from an inactive outdoor swimming pool. *Solar Energy, 53*(1), 3-7, doi:10.1016/S0038-092X(94)90597-5.

https://doi.org/10.1051/e3sconf/202236214004

Smith, C. C., Lof, G., Jones, R., Kittler, R., & Jones, R. (1998). Rates of evaporation from swimming pools in active use / Discussion. *ASHRAE Transactions, 104*, 514-523.

Verein Deutscher Ingenieure (2010). VDI 2089 - Building Services in swimming baths Indoor pools. (pp. Part 1, P.56): Engl. VDI-Gesellschaft Bauen und Gebäudetechnik.