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Quantifying the Influence of the Pool Cover on the Water Evaporation Rate in Indoor Swimming Halls

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Abstract

Swimming facilities represent a complex building category that require precise planning in the design phase for energy efficient operation and good indoor climate. This includes the use of building performance simulation tools for estimating energy use and designing the energy plant. The primary challenge in a swimming facility is managing the water surface and controlling the evaporation rate. In the design phase, this must be estimated by using empirical relationships and assumptions. For occupied and unoccupied pools, several empirical relationships are presented in the literature. This is not the case for pools using a moveable floor, a feature with increasing prevalence, as a pool cover. This article presents measurements and analysis of the evaporation rate for an indoor swimming pool in Norway. This includes the evaporation rate with the use of a moveable floor in the swimming pool as a pool cover. It has been found that the evaporation rate for an unoccupied indoor pool can be reduced by up to 70% with the use of this feature. This entails that the correction factor of the ASHRAE-equation can be reduced from 0.5 to 0.15 when this feature is activated.

Key innovations

- Indoor swimming pools
- Evaporation rate
- Energy simulation

Practical implications

The practical implications of the findings in this paper will help the simulation practitioner to improve the accuracy of the energy simulations of swimming facilities.

Introduction

Swimming facilities are among the most energy-intensive buildings (Kampel et al., 2013). Within these facilities, the process of water evaporation is recognized as the primary factor influencing energy consumption (Smedegård, 2023). This phenomenon occurs at the boundary layer between the swimming pool water and the indoor air, cooling the pool water while increasing the enthalpy of the indoor air due to the added water vapor. While the energy consumption due to evaporation is the main source of energy loss for outdoor swimming pools, for indoor swimming facilities, the magnitude of energy loss highly depends on the HVAC system concept, as the area normally has a fully indoor climate control system. By controlling both the airflow rate and the state of the supplied and extracted air, the indoor environment is controlled in indoor swimming pools. This control strategy is essential for maintaining thermal comfort and air quality and preventing issues such as condensation and corrosion (Smedegård, 2023). Consequently, for indoor swimming facilities, the air handling unit is identified as a crucial component for the overall operation of a swimming facility.

However, in swimming facilities located in cold climates, such as the Marine West Coast climate zone according to the climate zones definition in Köppen and Geiger climate system (Köppen & Geiger, 1930), thermal losses due to humid air are inevitable. Minimizing evaporation from the free water surface can reduce these losses. This can be achieved by optimizing the indoor environment, including airflow, temperature, and humidity (Shah, 2014), or simply by applying pool covers (Gomez-Guillen et al., 2024; Nouanegue et al., 2011).

Traditionally, pool covers involve a diffusion-tight plastic cover that is rolled out during nighttime or idle periods. While this cover completely stops evaporation, it presents challenges related to investment cost and maintenance. In recent years, modern swimming pools have increasingly incorporated movable floors, an additional component that makes the pools suitable for a wider range of activities and user groups. By installing a movable floor, the depth of the pool can be adjusted, enhancing its flexibility in terms of usage. Additionally, the movable floor can serve as a pool cover outside opening hours, reducing evaporation from the pool water surface. However, the literature lacks studies regarding the efficiency of this strategy. This article investigates the effect of this feature due to the reduced water vapour evaporation from the pool surface.

There is a wide range of studies regarding evaporation rates in swimming pools, where diverse empirical equations are presented. However, the proposed empirical relations in the literature are found to differ in results (Shah, 2014), and there is no consensus in this field (Smedegård et al., 2021). The correlation introduced by Carrier (1918) is derived from small-scale laboratory experiments and is one of the most widely used equations for estimating evaporation rates in swimming pools. This

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equation, based on Dalton (1802), is characterized by its simplicity and is endorsed by ASHRAE handbooks (ASHRAE, 2019). Although the original experiments involved only forced convection, the equation is commonly applied in scenarios with air speeds as low as 0 m/s. ASHRAE has further simplified the equation by setting the air speed variable to zero, making it suitable for estimating evaporation rates in occupied pools. Additionally, ASHRAE provides correction factors of the equation, called activity factors, tailored to different types of pools, recommending a 0.5 multiplier for unoccupied pools. Although this recommendation lacks citation in the literature, this equation is extensively utilized, including in the BPS tool IDA ICE's Pools extension (EQUA Simulation AB, 2022).

During the 1990s, Smith et al. (1993, 1994; 1998) evaluated the accuracy of Carrier's equation for both indoor and outdoor pools, whether occupied or unoccupied. Their findings indicated that the equation underpredicted evaporation rates for occupied pools and overpredicted them for unoccupied pools.

Smedegård et al. (2022) analysed the evaporation rate for both occupied and unoccupied operations in two swimming facilities in Norway. By normalizing and comparing the results with the ASHRAE's activity factor (ASHRAE, 2019), they found their results to comply with the recommended level for unoccupied pools. Like Smith et al., Smedegård et al. recommended new correction factors for occupied pools but introduced different correction factors depending on the type of simulation (i.e., when making an annual energy simulation and for peak load evaluation).

Based on the use of the correction factor in these studies, this paper investigates the evaporation rate using a moveable floor as a pool cover. The results are both analysed, and compared to, the ASHRAE correction factor. This will help the simulation practitioners in being more confident in their choice of input variables when calculating evaporation rate and energy use for swimming pool models in BPS tools.

Method

This article presents findings from a comprehensive, full-scale measurement campaign on the evaporation rate in swimming pools. The methodology can be summarized in a three-stage process:

- **Data Collection**: Gathering data on the evaporation rate and the surrounding indoor climate conditions.
- **Data Analysis**: Calculating the corresponding correction factor related to the ASHRAE equation.
- **Validation**: Comparing the proposed correction factors with those recommended in the literature.

The ASHRAE equation for calculating evaporation rate is given as Equation (1). For this equation, $\dot{m}_{evap}$ gives the evaporation rate [kg/s], A_{pool} is the area of pool surface [m^2], 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 correction factor [-].

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

The evaporation rate was experimentally investigated at the swimming facility in Fyret, located on the Norwegian island of Jøa, located 64.6 N, 11.2 E, 65 m above mean average sea level. Its climate zone is defined as Marine West Coast according to Köppen and Geiger (1930). Data collection and investigation were conducted from 10.01.2020 to 18.02.2020. Fyret at Jøa is a multipurpose centre serving a small community, and it includes various facilities such as a sports hall, an indoor shooting range, and a library. The centre is adjacent to an elementary school and kindergarten, which are the primary users of the facility.

Direct measurement of the evaporation rate is not feasible; it must be calculated. The research literature outlines several techniques and methods for measuring evaporation (Smedegård et al., 2022), including: (1) energy balance for the water circuit (Smith et al., 1998), (2) mass balance for the water circuit (Smith et al., 1993), and (3) moisture mass balance for the swimming hall (Hanssen. & Mathisen., 1990; Lu et al., 2014). This study employed the moisture mass balance method for the swimming hall, as illustrated in Equation (2). Figure 1 provides a generic illustration of the mass balance. Here, m_{room} [kg] represents the moisture content in the swimming hall, $\dot{m}_{sup}$ [kg/s] is the supplied moisture mass flow rate, $\dot{m}_{evap}$ [kg/s] is the water vapor mass flow rate due to evaporation, $\dot{m}_{inf}$ [kg/s] is the moisture mass flow rate due to air infiltration, and $\dot{m}_{ext}$ [kg/s] is the moisture mass flow rate by the extract air flow.

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

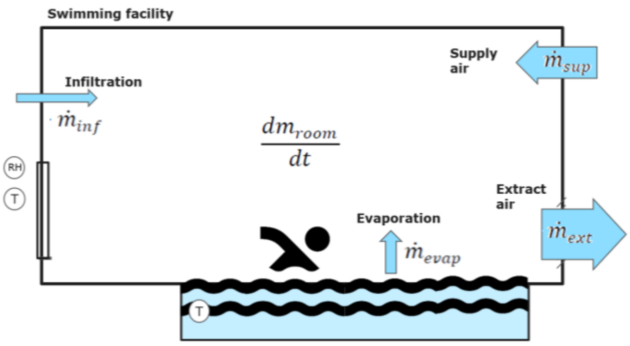

Figure 1 Schematic illustration of the key components affecting in the mass balance in the hall.

The dataset from the measurement campaign comprised a total of 215 hours of cleaned data. This data cleaning was required due to interruptions in the swimming sessions and the normal operation of the pool. The final dataset included 133 hours with the pool cover activated and 82 hours with the water surface exposed to the surroundings.

The swimming pool, previously used in research by Smedegård et al. (2021; 2022; 2023), is an educational pool with a water surface area of 100 m² and a length of 12.5 meters. During the day, the pool is used by pupils and children from the nearby school and kindergarten. In the evenings, the pool is rented out to individuals and organizations.

Table 2 presents the setpoints for the pool water temperature, room air dry bulb temperature, relative humidity, and nominal extract air volume flow rate for the facilities. These variables were continuously collected during the campaign. Table 1 summarize the variables with their respective unit and sources. The variables marked with "BAS" was collected from the Building Automation System, i.e. from the air handling unit's automation system. The air handling unit is a Menerga model 391301.

The movable floor in a swimming pool consists of a hydraulic lift system that adjusts the floor's height, allowing it to cover the pool or set it to various depths. This is operated fully manually, where the operator must "push and hold" the activation switch for the moveable floor when adjusting its height position.

Table 1 Summary of variables involved in the study.

Variable	Description	Unit	Source	Comment
$\dot{m}_{sup}$	Supplied moisture mass flow rate	kg/s	Calculated	By $\dot{V}_{sup}$, t_{sup} and RH_{sup}
$\dot{m}_{ext}$	Extracted moisture mass flow rate	kg/s	Calculated	By $\dot{V}_{sup}$, t_{sup} and RH_{sup}
$\dot{m}_{inf}$	Moisture mass flow rate, infiltration	kg/s	Calculated	By $\dot{V}_{sup}$, $\dot{V}_{ext}$, t_{sup}, RH_{sup}, t_{ext}, RH_{ext}, t_{out}, RH_{out}
m_{room}	Moisture content, swimming hall	kg	Calculated	By changes in air state over the time step
P_a	Vapor pressure at room air dew point	kPa	Calculated	By t_{room}, RH_{room}
P_w	Saturation pressure, pool surface	kPa	Calculated	P_{sat} at t_{pool}
$\dot{V}_{sup}$	Supplied air flow rate	m³/h	BAS	
$\dot{V}_{ext}$	Extracted air flow rate	m³/h	BAS	
$\dot{V}_{inf}$	Air flow rate, infiltration	m³/h	Calculated	Supply and extract air flow rate difference
t_{sup}	Dry bulb temperature, supply air	°C	BAS	
RH_{sup}	Relative humidity, supply air flow	%	BAS	
t_{ext}	Dry bulb temperature, extracted air	°C	BAS	
RH_{ext}	Relative humidity, extracted air	%	BAS	
t_{out}	Dry bulb temperature, outdoor	°C	Metrological data	
RH_{out}	Relative humidity outdoor	%	Metrological data	
t_{pool}	Pool water temperature	°C	BAS	

Figure 2 shows the swimming pools of Jøa with the moveable floor activated as a pool cover. This system enhances safety, versatility, and functionality, transforming the pool area into a multi-purpose space. Figure 3(a) and (b) illustrate the use of a moveable floor in a swimming pool.

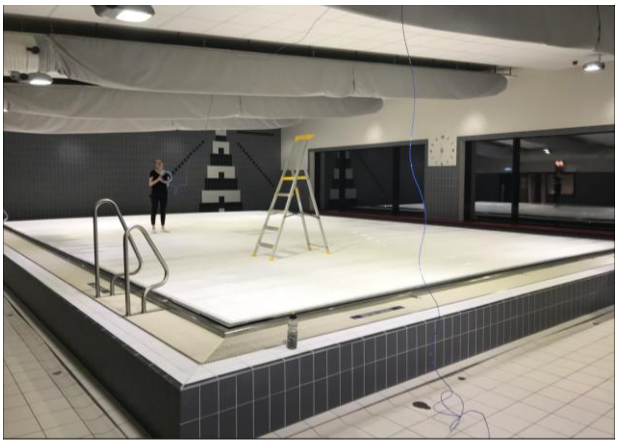

Figure 2 The swimming pool at Jøa with the movable floor activated as a pool cover.

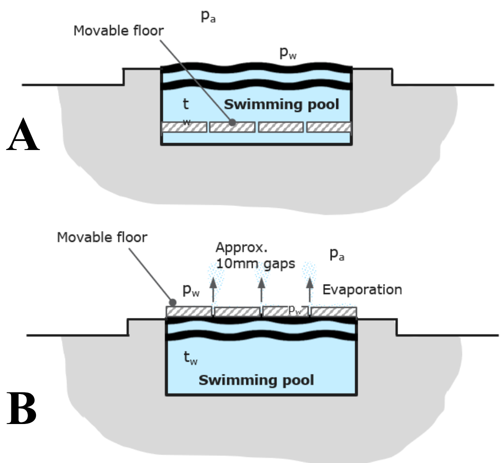

Figure 3 Moveable floor in a swimming pool. A generic illustration for A - bathing mode and B - idle mode.

Table 2 Set points for pool water temperature, room air dry-bulb temperature, and extract air volume flow rate for the swimming pool at Fyret, Jøa.

	Set-point
Pool water temperature	32 °C
Room temperature	31.5 °C
Room humidity	RH 55%
Air flow (day/night)	8200/6600 m^3/h

Results

Based on literature and recent research, the correction factor associated with the ASHRAE equation (ASHRAE, 2019) is 0.5 for an unoccupied pool. Figure 4 shows the calculated correction factor for the data collected during the measurement campaign with the moveable floor used as a pool cover. The calculation of the correction factor is based on hourly averaged evaporation data and by solving the ASHRAE-equation, equation (1), with respect to F_{act}.

When the movable floor is applied above the water surface, it is shown that the correction factor reduces to an average of 0.18. The values range from approximately 0.08 to 0.28, with a corresponding standard deviation at 0.05. This range corresponds to a significant reduction in evaporation compared to the baseline correction factor of 0.5.

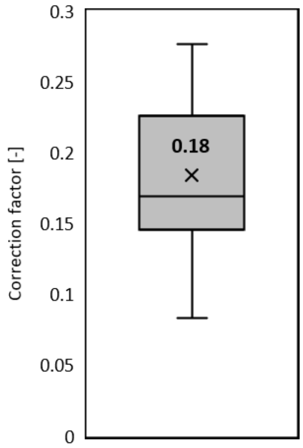

Figure 4 The calculated correction factor with the moveable floor used as a pool cover.

The experimental setup for data collection included both idle mode (typically at night) and bathing mode. These two operational phases is represented by different ventilation strategies, which significantly influence the indoor air state. In night mode, the system continuously dehumidifies and recycles the extracted air from the swimming pool, resulting in stable conditions with only minor deviations from the air humidity setpoint. For this facility, the deviation is due to the use of a P-controller in night mode. Additionally, the total circulated air flow in the facility is reduced to about 60% of the nominal air flow in idle mode.

In bathing mode, the system operates differently due to the fresh air demand from occupancy. Dehumidification in this phase relies solely on continuous air exchange with fresh air, with the flow rate controlled by the relative humidity of the extract air. The heat pump in this phase is controlled with a focus on energy efficiency. Due to occupancy, the system operates with a minimum fresh air flow and a total airflow rate of 80-100%, depending on the indoor air state in the swimming hall. Figure 7 presents the collected data for the period when the pool cover is activated, effectively illustrating the impact of imprecise management of the operation mode. During this data collection period only two swimming sessions occurred. This low user-intensity was due to the closure of the school and kindergarten for winter vacation. As illustrated in the figure, these two swimming sessions were unintended, as they took place when the air handling unit was either in idle mode (weekend) or partially in idle mode (late evening). Except for these two swimming sessions, the entire dataset represents data with the pool cover activated.

Figure 5, 6 and 7 present the normalized correction factor data separated by operation mode. Two distinct clusters are observed: idle mode (ACH 6.5 h^{-1}) with an average correction factor of 0.15, and bathing mode (ACH 8 h^{-1}) with an average of 0.23. The standard deviation within each cluster was 0.02. For comparison, the correction factor remains consistent between operation modes when the water surface is fully exposed, as shown in Figure 8.

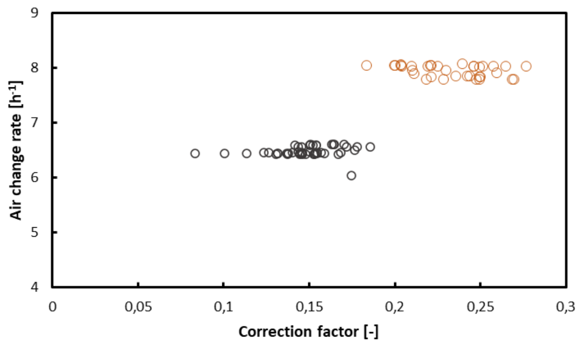

Figure 5 Scatter plot - calculated correction factor (ASHRAE equation) plotted against total air change rate

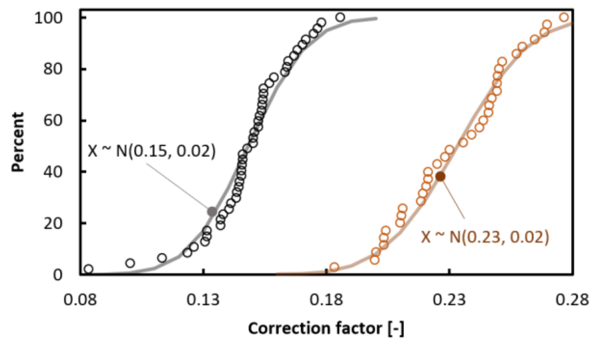

Figure 6 Empirical cumulative distribution function for the calculated correction factor. Black marker – AHU operated in idle mode. Orange marker – AHU operated in bathing mode. Standard normal distribution given with respective mean and standard deviation.

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Figure 9 compares and summarizes the calculated correction factors, presenting them alongside the air change rate for both covered and uncovered pool scenarios in both operation modes. The figure shows the evaporation. However, as shown in Figure 4, the collected data exhibit a large spread with a standard deviation of 0.05. This potentially correspond to range of reduced evaporation rate between 44% and 84% compared to the

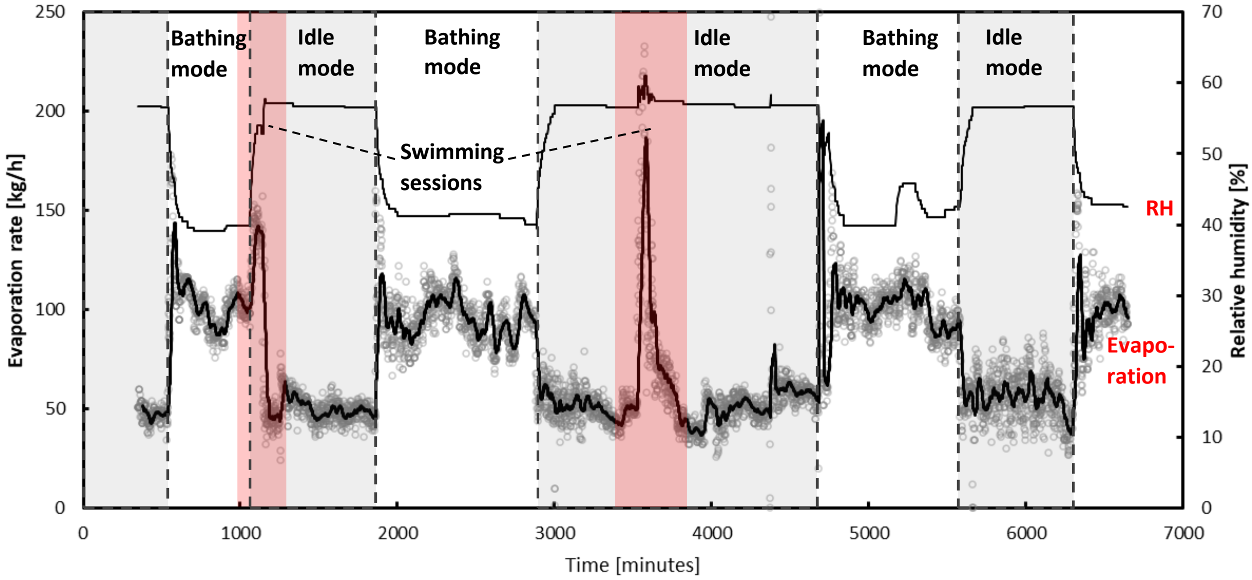

Figure 7 Data collection illustrated over the timeline - Extract air humidity, evaporation rate and operation mode. Grey area - idle mode; White area - bathing mode; Red area – swimming sessions

correction factor to deviate in the cases with the use of pool cover but remains consistent otherwise.

Finally, Figure 10 shows the actual versus intended position of the movable floor. Observations revealed that the floor was often slightly elevated above the water surface due to manual operation procedures.

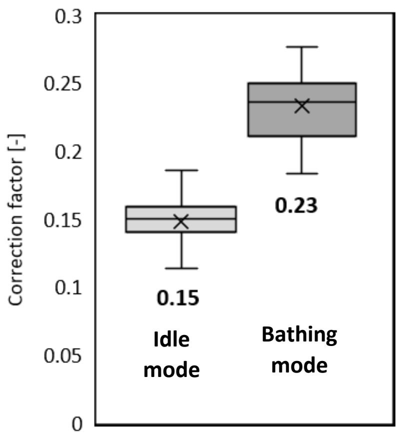

Figure 8 Box plot - calculated correction factors for idle mode and bathing mode, both with pool cover

Discussion

The results demonstrate that employing a movable floor as a pool cover leads to a significant reduction in evaporation. With an average correction factor of 0.18 for the covered pool—compared to the reference value of 0.5 for an unoccupied pool with a free water surface — this corresponds to an approximate 64% reduction in reference value of 0.5 for a free surface. This suggest that multiple factors influence evaporation beyond surface coverage alone.

The effect of the operation mode is evident: when operating the air handling unit in bathing mode, with increased fresh air intake and reduced relative humidity, the evaporation rate nearly doubles compared to idle mode. See Figure 4. In night mode, the RH-setpoint is shown to be achieved. However, this is highly dependent on outdoor conditions since it is related to the absolute humidity of the outdoor air. While this is beneficial for the building façade (since it reduces the differences in vapor pressure over the façade), it is energy-intensive and costly due to the increased evaporation.

Although this effect, of increased evaporation rate, is partly explained by the greater vapor pressure differences between water and air, normalization of the data suggests that other mechanisms may also contribute.

Figure 5 illustrates the normalized data, clearly showing two clusters depending on the facility's operation mode. The operating modes are defined as bathing mode (ACH 8 h^{-1}) and idle mode (ACH 6.5 h^{-1}). Figure 8 presents data for these two clusters. The correction factor for bathing mode operation averages 0.23, while for night mode, it averages 0.15. This difference suggests that additional factors besides the operation of the AHU affect the evaporation rate. The part of the distinction between the two operation modes is related to the total air flow rate but this difference is shown not to influence the evaporation rate, when the water surface is exposed to the room air. See Figure 9. For scenarios without a pool cover, the

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correction factor remains consistent regardless of the operation mode.

Further on, it was found during the campaign that the movable floor was often lifted slightly above the water surface, even though the optimal and intended use includes a position at the pool surface. Figure 10(a) and (b) illustrate the optimal position and observed position. This misplacement is due to the manual operation of the movable floor, where the operator manually adjusts the level by continuously holding the switch for security reasons. No sensor, or alarm, is making the operator aware

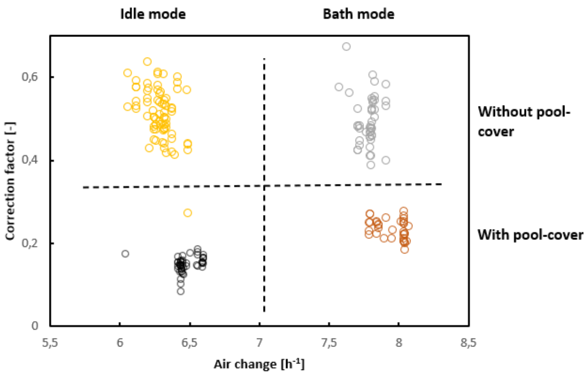

Figure 9 Calculated correction factors for scenarios with and without pool cover, both operated in idle mode and bathing mode

of the actual position is installed in the facility. Although this increases the evaporation rate, it also suggests that even the lowest correction factor (in night mode) could be further reduced if the upper position of the movable floor is optimized, for example, by using sensors and automation. Implementing automated control or feedback systems could further lower the correction factor in night mode and improve overall energy performance.

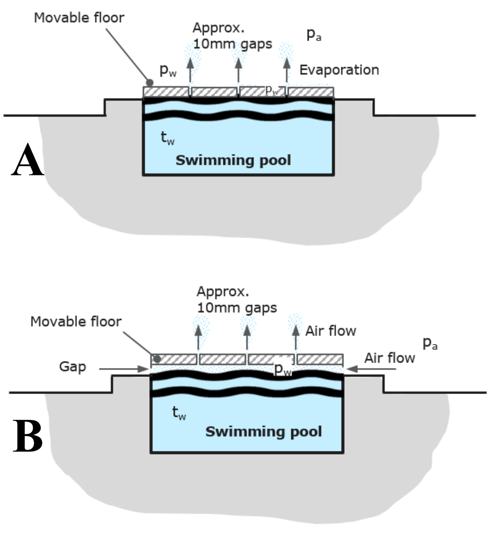

Figure 10 Positioning of the movable floor in operation. A - optimal position, B - observed position.

When the pool cover is positioned above the water surface, it creates an air gap between the water surface and the cover. Due to slots between the horizontal plates of the floor and a vertical gap surrounding the pool, a circulating air flow is facilitated under the pool cover due to the stack effect. Bathing mode, which entails lower relative humidity in the swimming hall, entails a larger difference in air density, driving the air change and airflow between the water surface/pool cover and the surroundings.

Despite these operational limitations, the findings highlight the potential of using the movable floor as an effective evaporation control measure. With proper deployment, evaporation may be reduced by up to 70%, which can translate directly into energy savings—particularly in facilities without heat recovery systems or in outdoor pools where exhaust air energy is lost. However, additional measurement campaigns should be carried out, investigating the transferability of the findings by investigating other facilities and seasons.

Conclusion

Swimming facilities represent a complex building category that requires precise planning during the design phase. This includes the use of building performance simulation tools to estimate energy use and design the energy plant. The primary challenge in a swimming facility is the water surface and evaporation and how to control these within the desired range. Accurate correlations for the evaporation rate are essential for precise results in the design phase. Energy simulation software employs various equations, e.g., IDA ICE using the widely known ASHRAE equation, derived from the Carrier equation. When estimating evaporation with this equation, the so-called correction factor defines the pool's overall usage, or level of activity. ASHRAE provides a set of recommended correction factors, known as activity factors, for use with Equation (1). However, there is no factor specifically defining the use of a pool cover or, more specifically, a movable floor as a pool cover.

Movable floors are widely used in Norwegian swimming pools, particularly in school pools (12.5 x 8 meters) and training pools (25 x 12.5 meters). Their use is increasing as they significantly expand the pool's user group.

In addition to their functional benefits, movable pool floors can also serve as an energy efficiency measure. By elevating the pool floor just above the water surface, the water evaporation rate - and consequently the energy required to heat the pool - can be reduced. Measurements and estimates of water evaporation for both exposed water surfaces (unoccupied) and with a pool cover indicate that, under optimal conditions and in a well-operated facility, a 70% reduction in evaporation rate, and therefore the energy demand, is achievable. In the design phase this means that the correction factor represented in the ASHRAE equation can be reduced from recommended 0.5 for unoccupied pools to 0.15 with the use of the moveable floor as a pool cover.

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However, achieving the abovementioned reduction in evaporation and energy demand requires strict control of the indoor climate. Bathing mode should only be activated when the pool is in use, which is not always the case in Norwegian swimming halls where daytime is equated with bathing time, even if the pool is unoccupied.

Another important consideration is the placement of the pool cover (movable floor) when it is in its top position. It is preferable to align the level with the water surface, as any gap underneath the pool cover can facilitate air exchange with the surroundings, increasing the evaporation rate. Addressing this issue is a minor task for future suppliers of movable floors in swimming facilities. Utilizing this feature helps swimming facilities approach the goal of sustainable design.

Acknowledgement

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