

ENHANCING THERMAL PERFORMANCE IN SWIMMING POOLS THROUGH HEATING TECHNOLOGY OPTIMIZATION

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Abstract

Swimming pool heating (SPH) is crucial for extending the swimming season and enhancing the overall pool experience. This study examines the optimization of heating technology in swimming pool facilities, targeting improved energy efficiency, reduced operating costs, and enhanced thermal comfort. Swimming pools require consistent heating, especially in colder climates, resulting in high energy consumption. Through an integrated analysis of passive and active heating technologies including solar thermal systems, heat pumps (HP), geothermal energy, and waste heat recovery, this paper develops a framework for assessing and optimizing swimming pool heating systems. A mathematical model was developed to simulate heat loss and gain across various system components. The results show significant improvements in system performance with combined strategies, increasing the Coefficient of Performance (COP) from 0.00 to 9.93, indicating a system with higher energy efficiency. This paper proposes an optimized SPH design methodology and highlights the impact of strategic system configuration on energy conservation and cost-effectiveness.

Keywords: Energy Optimization, Heating Technology, Renewable Energy, Swimming Pool Heating, Thermal Efficiency

I. INTRODUCTION

Aquatic facilities, including swimming pools of various types, are commonly perceived as venues for recreational activities, relaxation, and physical exercise in regions characterized by temperate and frigid climates. Throughout most annual periods, specialized systems regulate the thermal and humidity parameters alongside pool water temperatures. Within enclosed swimming facilities, water temperatures are generally sustained between 26°C and 30°C for competitive and recreational purposes, with potentially elevated temperatures for young children, while ambient air temperatures are maintained 2°C above water temperature according to facility function. Consequently, the atmospheric temperature within pool environments exceeds that of conventional public areas by approximately 10°C to 15°C.

Energy is a basic requirement of modern life and also a precondition for the development of industries in many respects, including agriculture, transportation, telecommunication, and digitalization (Xie *et al.*, 2018; Li *et al.*, 2020). The energy crisis is becoming more and more serious, as fossil fuels are continuously utilized, leading to environmental pollution problems (Such as global warming and ozone depletion) (Du

et al., 2018). Studies have shown that energy use in swimming pool facilities can range from 600kWh/m² to 6,000 kWh/m² annually, depending on pool type, climate, usage schedule, and heating technology employed (TriantiStourna *et al.*, 2008; Kampel *et al.*, 2013).

The primary energy consumption in swimming pool facilities is attributed to heating requirements. Nevertheless, the heating demands for ISP and OSP installations vary as a consequence of ambient temperature conditions. Research reveals that annual energy data collection for 41 Norwegian ISP facilities from 1998 to 2011 is estimated to be 3991kWh/m². However, during the cold season, especially in subtropical climate regions, the OSP is closed due to undesirable weather (Li *et al.*, 2020). Within densely populated urban environments such as Hong Kong, spatial resources hold significant value, making the shutdown of OSPs result in inefficient space utilization. Consequently, thermal systems become essential to extend operational periods for OSPs during colder months. Furthermore, the implementation of sophisticated heating technologies for aquatic facilities is imperative. Nevertheless, an exhaustive examination of appropriate and cutting-edge heating technologies utilized in swimming pool installations remains absent. There exists a critical need to address the knowledge deficiencies in formulating thermal transfer models for aquatic facilities and the engineering and management of SPH systems.

This study therefore provides a comprehensive examination of sophisticated heating technologies employed in swimming pool applications. Initially, the mathematical frameworks developed to characterize thermal transfer mechanisms within swimming pools are outlined, encompassing thermal losses through evaporation, convection, conduction, radiation, and water replacement, alongside solar thermal gains. Various empirical formulations and methodologies for describing the principal elements of swimming pool modeling are detailed. Secondly, the technologies employed in SPH systems are categorized into passive and active approaches. Active technologies are further subdivided into ISP and OSP heating methodologies. ISP heating methodologies encompass solar collectors, HP, waste heat recovery, and Geothermal Heat Energy (GHE) technologies. OSP heating methodologies comprise solar collectors, HP, Phase Change Materials (PCM) storage, GHE heat storage, biomass heaters, and waste heat recovery technologies. This research exposition is grounded in practical applications and prospective research directions to assist researchers in formulating appropriate and pertinent SPH systems.

The energy consumption patterns of outdoor swimming pools (OSPs) are predominantly influenced by external climatic factors, whereas indoor swimming facilities exhibit different characteristics, with their energy usage primarily governed by thermal supply systems (including space heating, supply air heating, DHW heating, and pool water heating) as well as electrical requirements for sauna operations and ventilation system dehumidification processes. The heating supply ensures both comfortable water temperature, and indoor thermal comfort levels, while the dehumidification process adjusts high humidity caused by inevitable water evaporation to an occupant's acceptable level (Chow *et al.*, 2012).

Optimizing heating technology in swimming pools is crucial for promoting better energy utilization, reducing operational costs, and ensuring user comfort. Swimming pools, whether for residential,

commercial, or public use, require consistent heating to maintain a comfortable temperature. The heating process is energy-intensive, and inefficient systems can lead to significant energy waste and high costs. This research focuses on identifying and addressing the key problems associated with optimizing heating technologies in swimming pools with the introduction of available heat transfer models to calculate or predict heat loss and gain for swimming pools, which is essential for optimizing heating systems in various passive and active heating technologies used for both ISPs and OSPs, and to help develop a mathematical and empirical model for evaluating heat loss and gain in indoor pool environments.

II. MATERIALS AND METHODS

Figure 1 illustrates the configuration of the suggested decentralized ventilation framework incorporating an air distribution network and the swimming pool's AHU equipped with a HP. When the facility utilizes a decentralized approach, the swimming area will be segmented into distinct zones, representing areas with varying parameter specifications regarding temperature and relative humidity conditions.

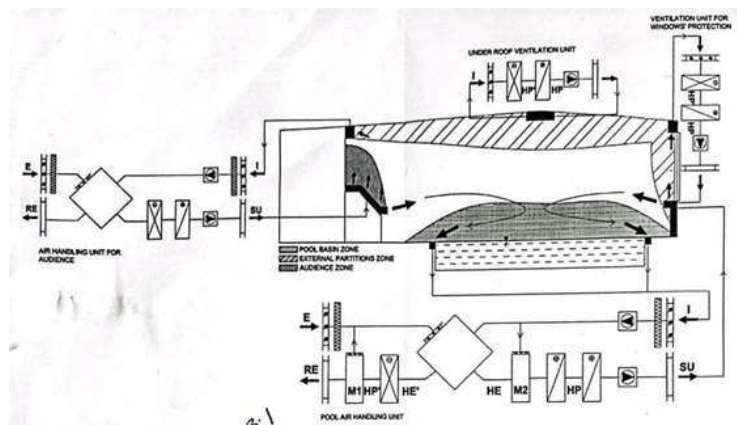


Figure I: Decentralized ventilation system Ratajczak and Szczechowiak, (2020)

Fresh air must be introduced to the swimming pool basin situated within this area to eliminate moisture accumulation and volatile chlorine compounds (disinfection by-products from pool water treatment) that develop in this location. This objective can be accomplished through an appropriate air circulation system as illustrated in Figure 2.

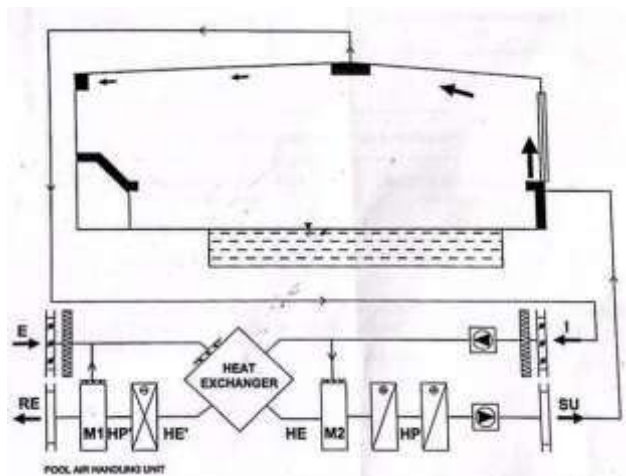


Figure II: Centralized ventilation system for swimming pool (Ratajczak and Szczechowiak, 2020)

2.1 Mathematical Model of ISPs

Heating Ventilation and Air Conditioning systems in ISP buildings are designed to provide suitable thermal comfort conditions for pool users in the SPH areas (Shah, 2002). Indoor temperature is kept at relatively high levels 24°C to 29°C , creating conditions for significant evaporation rates from the pool water surface (Ribeiro *et al.*, 2016). Figure 3 illustrates the primary sources of energy dissipation in an indoor SPH, including thermal conduction through pool boundaries Q_{cond} , convective heat transfer from the water surface Q_{conv} , radiative heat emission from the pool surface Q_{rad} , evaporative losses from the surface Q_{Evap} , thermal losses associated with fresh water replacement Q_{fw} to compensate for water depletion, and auxiliary heating energy input Q_{aux} .

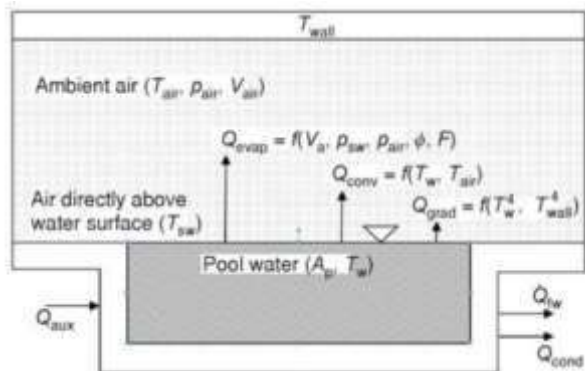


Figure III: Swimming pool energy balance model scheme (Moncic *et al.*, 2014)

The dynamic evaluation process begins with the formulation of mathematical models that represent the energy balance within the swimming pool (Echendu *et al.*, 2024). It is a sophisticated approach that examines the performance of these systems under varying environmental conditions, such as fluctuating solar radiation and changing ambient temperatures, (Echendu *et al.*, 2024). A balanced model of an ISP presented in-takes into account air infiltration losses of the SPH and outside air intake, but it neglects

radiation heat transfer and losses due to fresh water supply. The temperature change of p_w over time t can be calculated as shown in equation 2.1:

$$\rho_w C_{pw} V_p \frac{dT_p}{dt} = Q_{aux} - (Q_{fw} + Q_{conv} + Q_{evap} + Q_{rad}) \quad (2.1)$$

Evaporation heat losses are proportional to the flow of water evaporated from the swimming pool water surface:

$$Q_{evap} = A_p \cdot E \cdot r \quad (2.2)$$

Where;

E - mass flow rate of evaporated water (kg/s) and r - the latent heat of evaporation (J/kg)

2.2 Heat Transfer Model of the Swimming Pool

An SPH transfer model constitutes a fundamental prerequisite for examining SPH system performance. This model aims to characterize pool water fluctuations through the overall thermal flux within the pool, encompassing solar heat acquisition alongside thermal losses via evaporation, convective processes, conductive mechanisms, radiative transfer, and water replenishment. The mathematical expression for this model was documented in research conducted by Ruiz and Martinez (2010) and Wooley et al. (2011), as demonstrated in equation 2.3.

$$P_w \times C_w \times V_p \times \frac{dT_p}{dt} = \sigma_{i0} \cdot Q_s - Q_e - Q_{cv} - Q_{cn} - Q_r - Q_{rf} \quad (2.3)$$

Where;

P_w - Density (kg/m³)

C_w - Specific heat of the water (J/(kg·K))

V_p - Volume of water (m³)

T_p - Temperature of water (°C) in the swimming pool. σ_{i0} - Constant for distinguishing ISPs and OSPs. For ISPs, $\sigma_{i0} = 0$, while

For OSPs, $\sigma_{i0} = 1$.

Q_s - Heat obtained from the sun (W)

Q_e , Q_r and Q_{rf} - Heat loss from the evaporation, convection, conduction, radiation and refilling water respectively.

T - Time (s)

i.) Heat gain from the sun: In indoor swimming pool facilities, solar radiation is absorbed by the structural elements of the building, consequently influencing the ambient air temperature within the space. This phenomenon impacts the thermal exchange processes occurring between the pool water and the surrounding air. Nevertheless, since the pool water cannot receive direct solar thermal input, the solar heat gain (Q_s) is excluded from the thermal transfer calculations for indoor swimming pool systems Lam

and Chan, (2001). Conversely, in outdoor swimming pool installations, solar radiation can be directly captured by the water surface. The solar heat gain Q_s is mathematically represented through equation 2.4.

$$Q_s = \alpha_s \times G_s \times A_p \quad (2.4)$$

Where:

G - Solar irradiation (W/m^2) and α_s - Solar absorptivity, which is assumed to be 0.85 in the studies of (Lam and Chan, 2001). **ii) Heat flow directions in different zones:** Exterior partition area – the region adjacent to the external walls where genuine condensation occurs. Implementation of internal recirculation units for partition protection necessitates dehumidification of air originating from the pool chamber. The spectator area requires isolation due to the distinct comfort requirements of clothed observers compared to swimmers. This decentralized ventilation approach for aquatic facilities contrasts with conventional (centralized) systems that employ a single AHU to supply thermal requirements for the complete pool facility and operate continuously throughout the year, whereas decentralized configurations allow individual units to function solely upon demand.

2.3 Model Calibration

During the geometric modeling process, the structure underwent simplification and was partitioned into five distinct thermal zones: the pool area, changing facility, storage space, nonheated chamber, and the hall/bar section. These zones were categorized based on comparable thermo-hygrometric properties, with a visual illustration of this segmentation presented in Figure 4.

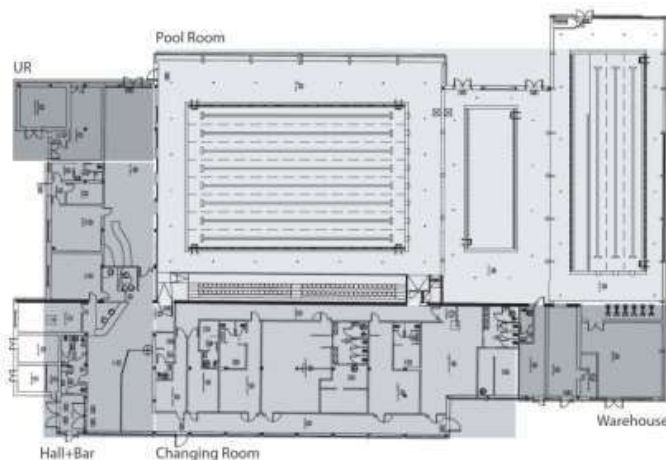


Figure IV: Swimming centre thermal zone (Alessia *et al.*,2020)

Regarding the swimming pool area, the centre is composed of three different pools, but to reduce the complexity of the model, it was implemented by using a single pool characterised by average values in terms of water temperature and depth. Table 1 describes the pool's characteristics, and the characteristics of the modelled one.

Table I: Pool Characteristic

Pool	Depth (m)	Surface (m ²)	T Water pool (°C)
Big	1.60	400	28.5
Medium	1.30	190	30
Small	0.60	80	31
Modelled pool	1.47	670	29

For model calibration purposes, obtaining data regarding temperature and working fluid mass flow rate was essential. Although the pool facility was already fitted with a Programmable Logic Controller (PLC) that enables working fluid temperature monitoring, data analysis revealed that the thermocouples integrated with the PLC lacked accuracy and were numerically inadequate for comprehensive system characterization.

Additionally, air temperatures across the five thermal zones, along with DHW and pool water temperatures, were recorded to establish initial conditions and perform model calibration. These temperature values were documented in Table 2(a) to enable the control system to regulate the SPH system for achieving stable temperature maintenance. An identical procedure was implemented for the power consumption of system components, as presented in Table 2(b) and

Table II(a) Air and Water Temperature

Description	Zonal/Elements	Value and Unit
Air Temperature	Pool room	30°C
	Changing room	26°C
	Hall + Bar	20°C
Water Temperature	DHW	42°C
	Pool	29°C

Table II(b) System components power

Description	Zonal/Elements	Value and Unit
Power	Boiler	540KW
	Cogenerator	80KW
	HX DHW	150KW
	Radiators	10KW
	Fan-Coil	10KW
	AHU	90KW

40KW Pool 620KW HP

Examining the thermal conditions across the three heated spaces - the entrance lobby featuring the bar area, the changing facilities, and the pool chamber - demonstrates that the model results align with the specified comfort criteria. Notably, the air temperature within the pool chamber remains within approximately 1°C to 2°C above the pool water temperature, adhering to established standards. The AHU operations maintain the air temperature in this zone at a minimum of 30°C.

III. RESULTS AND CONCLUSION

3.1 Presentation of Results

i) Reduction of evaporation rate: The Type 344 configuration enables users to incorporate a covering layer. Figures 5 and 6 present the model's results for an idealized scenario where the isothermal cover possesses zero thermal conductivity ($\lambda=0$ W/(mK)). Figure 5 demonstrates that air temperatures across different spaces generally maintain acceptable comfort parameters, with occasional exceptions. Certain irregularities occur immediately prior to boiler activation.

These irregularities arise due to the non-modulating nature of the condensing boilers, which generates computational anomalies in the numerical analysis. Consistent with the initial simulation, the hall/bar zone maintains approximately 20°C during operational periods and experiences temperature decline upon fan coil deactivation.

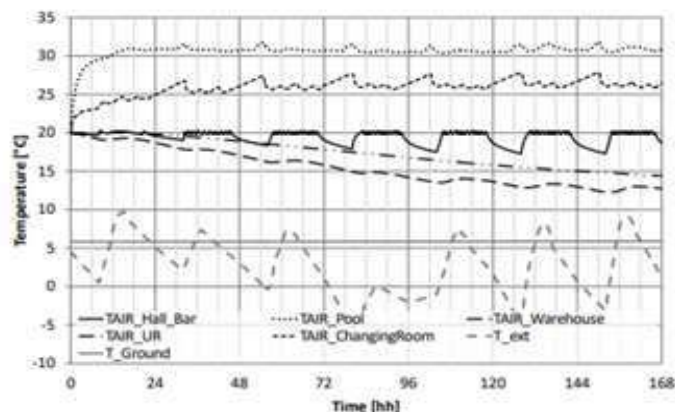


Figure V: Thermal zones air temperature, outdoor and ground temperature

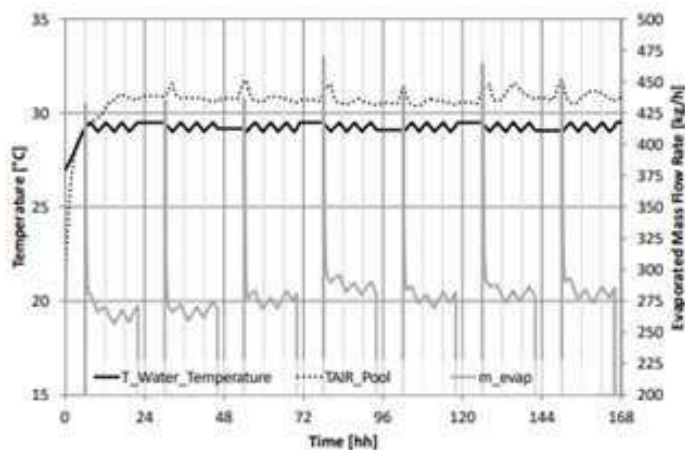


Figure VI: Pool water temperature and evaporated mass flow rate behaviour.

The water evaporation rate E_e from the pool surface exhibits substantial deviation from actual conditions, as demonstrated in Table 3. Under this theoretical scenario, where the covering material possesses zero thermal conductivity [0 W/(m.K)], nocturnal water evaporation from the pool is entirely prevented.

Table III: Summary of the empirical equation of E_e

References	Equations (unoccupied pools)	Equations (Occupied pools)
Hanssen and Mathisen	$E_e = 3 \times 10^{-5} \cdot W_e^{1/3} \cdot (e^{0.06TW} \cdot R_e \cdot e^{0.06T_a})$	-
Shah 2003,2014 (general forms)	$E_e = y_e \cdot (\Delta p)^n$	-
Shah 2002, 2003	$E_e = K_e \cdot \rho_{sw} \cdot (\rho_t - \rho_{sw})^{1/3} \cdot (S_{wx} - S_r)$ $((\rho_t - \rho_{sw}) > 0)$	$E_e = 0.113 - 7.9 \times 10^{-5} + 5.9 \times 10^{-5} \cdot D_p$
Shah 2012	$E_e = 0.00005 \cdot \Delta p \cdot ((\rho_t - \rho_{sw}) \leq 0)$	-

ii) Pool preparation: Environmental temperature conditions and wind velocity significantly influence swimming pool design parameters, with these effects being particularly evident in outdoor installations. Wind velocity impacts become more apparent during usage periods as a result of evaporative processes. Figure 5 demonstrates the fluctuation in overall heating requirements as calculated using equation 2.4. The findings indicated that reduced design ambient temperatures of 10°C produced the maximum load requirements, while higher temperatures yielded the opposite effect.

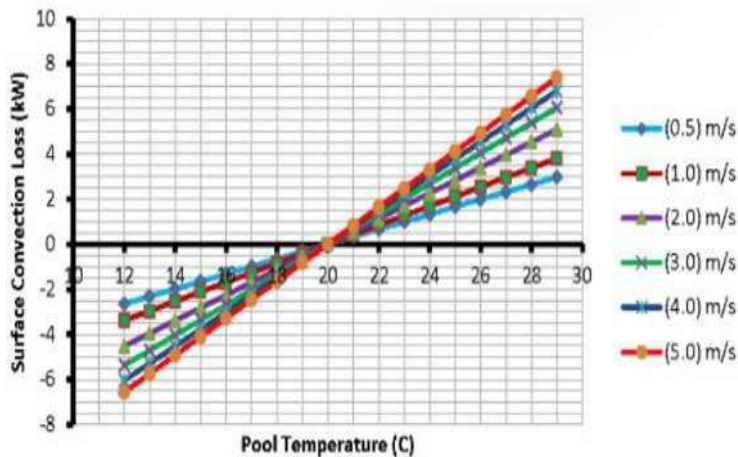


Figure V: Comparative analysis of preparation heating load across varying ambient air temperatures.

Figure 6 illustrates the characteristics of the surface convection element in relation to wind velocity and pool temperature under different ambient temperature conditions. The analysis clearly demonstrates that the system exhibits two distinct thermal modes: either thermal energy dissipation from the pool or thermal energy acquisition by the pool.

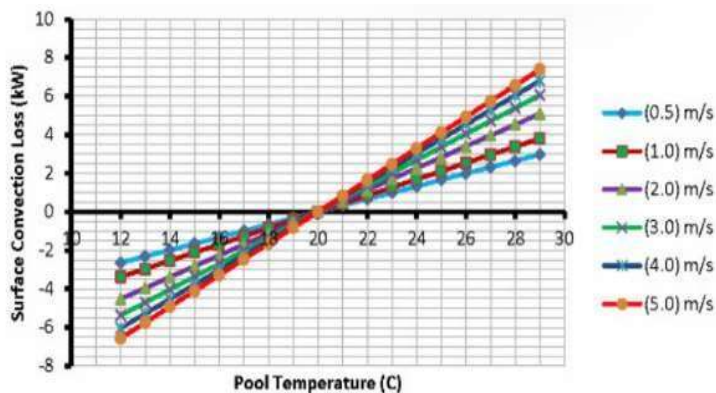


Figure VI: A comparison of the pool surface convection during preparation stage. The results also showed that the loss or gain were proportional to the wind speed, the higher usually corresponded to the

3.2 Preheating Process

With a known heating demand and an equation that explains the procedure during this phase, the constructed model for the first pool preparation is still applicable. The pool should be able to be reheated for the bathers' usage the following day by the design heating load that was selected from the (HEATING) code and implemented for the (USAGE) code. The computation of the mean heat loss at the pool temperature of 24°C to 29°C was taken into consideration in a process akin to that recommended for the occupancy stage assessment. For every wind speed, the average values of heat loss to the surrounding air, surface convection, pool wall, and radiation were calculated. The preheating procedure was selected to

occur at 15°C, which is the scheme's design ambient temperature. This was done in order to let the pool lose energy to the surrounding air for the entire range of pool temperatures following the occupancy stage, as shown in Figure 7.

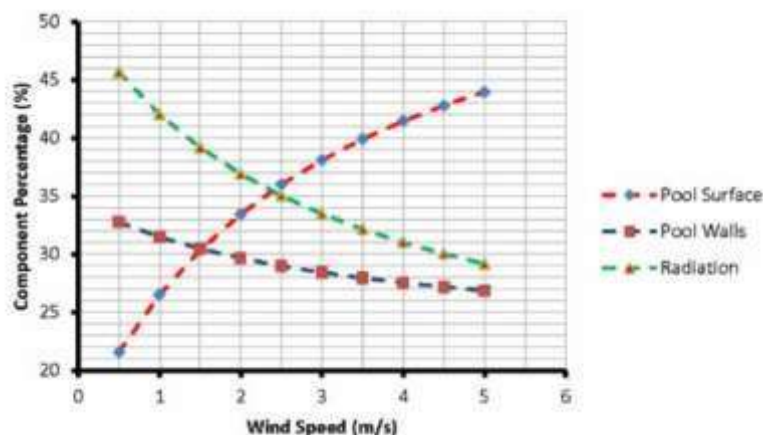


Figure VII: Predicted loss percentage at 15°C climate temperature for preheating stage. At wind speeds ranging from 0.5 m/s to 5 m/s, the surface convection loss accounted for roughly 22% to 44% of the overall loss. Convection-conduction loss from pool walls ranged from 27% to 33%, with the lowest wind speed corresponding to the greatest limit and vice versa. The corresponding radiation loss values ranged from 29% to 46%. The time needed to heat the pool to the design set temperature of 29°C was estimated using the equation. Polynomial formulas for the pool temperature variation with wind speed were found by analyzing the trend of the results. Equations 3.1 and 3.2 of the formulation for the 4-hour usage time are as follows:

$$\Theta_{\text{preh}} = 0.1413 u_{\text{wind}}^2 + 2.0362 u_{\text{wind}} - 1.2654 \quad (3.1) \quad \text{If the pool was used for 5 hrs swimming, then:}$$

$$\Theta_{\text{preh}} = 0.1766 u_{\text{wind}}^2 + 2.5453 u_{\text{wind}} - 1.5818 \quad (3.2)$$

The duration for preheating derived from these equations is expressed in hours. When utilizing a standard design wind velocity of 4m/s, the preheating duration ranged between 9.2 and 11.5 hours corresponding to occupancy periods of 4 and 5 hours respectively. Figure 8 presents a comparative analysis of the preheating duration required for the pool to reach the target temperature of 29°C across both models.

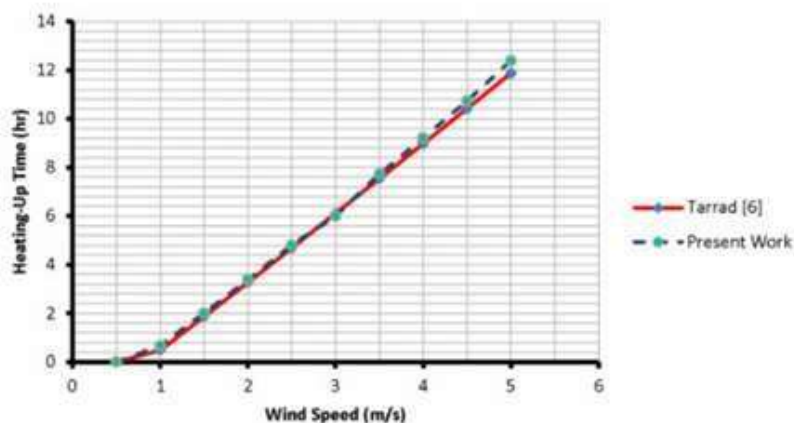


Figure VIII: Heating comparison of the model at ambient temperature during preheating.

3.3 Free Energy from HP

Large volumes of water in swimming pools need to be maintained at a specific temperature. When a heat exchanger and water-to-water HP are used together, a renewable energy source can provide the heat required to raise the water temperature to the desired level and then maintain it. Significant energy savings are made possible by this after filling the first DHW storage tank with water from the water network, the HP preheats it and maintains its average temperature between 20°C and 25°C. The suggested method uses a water-to-water HP's continuous running to keep the pool's water temperature stable at night.

3.4 Result Model Validation

It is feasible to determine the relationship between each machine's primary energy consumption and thermal efficiency by knowing the rated efficiencies of thermal machines. Table 4 shows the rated efficiency and consumption of the condensing boiler, cogenerator and HP.

Table IV: Efficiency, primary energy consumption and thermal output of each thermal machine

	Efficiency	KWh _{thermal} of fuel	KWh _{thermal}
Condensing boiler	105.6%	1	1.065
Cogenerator	$\eta_{\text{cogen}} = 82\%$ (thermal: 52%, electrical:30%)	1	1.42
HP	$\text{COP}_{\text{HP}} = 3.4$		
Total		2	2.485

This also shows that achieving a thermal output of 2.485 kWh_t requires the system to consume 2 kWh_t of gas input. Consequently, the conversion coefficient equals 0.805. Using this coefficient, one can establish the transformation from natural gas [kWh] to thermal [kWh], thereby enabling comparison between the natural gas consumption pattern derived from the pool's billing records and the consumption pattern generated through dynamic simulation analysis.

IV. CONCLUSION

This study presents a comprehensive analysis of the optimization of heating technology in swimming pools using integrated simulation models. Three distinct heating configurations were analyzed: a conventional boiler system, a solar-assisted HP system, and a hybrid geothermal-solar HP system. The results demonstrate that combining passive solar collection and active HP technologies substantially improves energy efficiency and thermal performance. The hybrid configuration emerged as the most efficient system, achieving a COP of 4.95 and reducing energy consumption by 66% relative to the conventional setup. Additionally, this configuration maintained superior temperature stability and contributed to substantial environmental benefits, including reduced carbon emissions. Although initial costs were higher, the long-term energy savings offered a favorable payback period, confirming the system's economic viability.

The findings highlight the importance of integrated design in optimizing SPH systems. Key contributions of the research include the development of a mathematical heat transfer model tailored for indoor pools, comparative performance evaluation of advanced technologies, and a practical guideline for deploying hybrid systems in energy-intensive swimming facilities. In addition, it merits significant emphasis that employing a modeling methodology enables the assessment of multiple energy conservation strategies. Such an approach facilitates the execution of reproducible analyses, adapting the numerical system to different swimming centres configuration, investigating their efficiencies and identifying opportunities for energy reduction interventions.

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