

PASSIVE SOLAR THERMAL SYSTEMS FOR OUTDOOR SWIMMING POOLS: THERMAL MODELLING, EXPERIMENTAL INVESTIGATION AND ENERGY EFFICIENCY

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Abstract: This study investigates passive solar heating of outdoor swimming pools through combined thermal modeling and experimental evaluation. A Python-based lumped-parameter model was developed and calibrated with simulated sensor data to predict water temperature dynamics. Results show that high-absorptivity absorber plates significantly increase pool water temperature, while overnight covers reduce heat losses. Sensitivity analysis highlights the influence of absorber area, coating type, and cover usage on thermal performance. Findings demonstrate that passive solar systems provide an energy-efficient and cost-effective strategy for sustainable pool heating.

Keywords: *Passive solar heating, Outdoor swimming pool, Thermal modeling, Experimental validation, Energy efficiency, Solar radiation, Water temperature distribution, Heat transfer analysis, Renewable energy utilization, Sustainable thermal system.*

1. INTRODUCTION

Outdoor swimming pools represent a significant portion of the energy demand in recreational facilities, particularly when heating is required to maintain thermal comfort. Traditional fossil-fuel or electrical heating systems incur high operating costs and carbon emissions. Solar energy offers a clean, renewable alternative, especially when leveraged with passive system designs. Recent literature highlights growing interest in solar-based pool heating systems, but comprehensive models and validated experiments remain limited. The aim of this research is to evaluate passive solar thermal systems for outdoor pools via experimental setup and numerical modelling, identify critical design parameters, and assess energy and economic performance.

1.1 Background and relevance

Maintaining a comfortable water temperature in outdoor pools often demands high energy input, especially in temperate climates. Solar thermal technologies—such as unglazed collectors, absorber plates, or polymer mats—have been utilised for decades to reduce energy consumption. For example, a state-of-the-art review by Li et al. (2021) summarises heat transfer models and active/passive technologies for swimming pool heating [1].

Despite available research on collector systems, specific studies on passive absorber configurations on pool bottoms or sides, combined with high-frequency data logging and model calibration, are scarce [2].

1.2 Research objectives and tasks

Objective: To investigate the thermal behaviour and energy-efficiency of passive solar thermal systems for outdoor swimming pools, and to derive practical design guidelines through experimental and numerical methods [3].

1. Conduct literature review of solar pool heating technologies and modelling approaches.
2. Design and build experimental test modules with different absorber variants for an outdoor pool.
3. Implement sensor logging system (DS18B20 \times 5, ambient measurements) with 5-minute intervals.
4. Develop a Python-based energy balance model of pool water temperature dynamics.
5. Calibrate model to experimental data and perform sensitivity analysis on design parameters.
6. Carry out techno-economic assessment including payback and cost of heat (LCOH).
7. Formulate recommendations for absorber material/type, installation, insulation, and cover usage.

2. Literature review

This chapter presents a review of existing studies on swimming pool heating systems, emphasising outdoor pools and passive/solar thermal solutions. Li et al. (2021) provide a comprehensive review of heat transfer models and pool heating technologies, noting that active heating (solar collectors, heat pumps, PCM storage) is widely investigated, whereas passive systems for outdoor pools need further work. [1]

Jiménez-Carrillo et al. (2015) review applied models for pool heating systems, highlighting the importance of conductive, convective, radiative and evaporative losses. [4]

Additional sources report that unglazed collector systems are cost-effective and suitable for warmer climates where major temperature rises are moderate. [5]

However, gaps remain in high-resolution modelling of absorber plate materials (e.g., aluminium, nano-coatings) and calibrated experiments in real pool environments.

3. Theoretical foundations and thermal modelling

3.1 Energy balance model

We adopt a lumped-parameter model of pool water temperature dynamics [6]:

$$m_c c_w \frac{dT_w}{dt} = Q_{abs} - Q_{evap} - Q_{conv} - Q_{rad} - Q_{out} \quad (1)$$

Where m_c - is the water mass (kg), c_w specific heat capacity ($\sim 4186 \text{ J kg}^{-1} \text{ K}^{-1}$), T_w - water temperature ($^{\circ}\text{C}$), Q_{abs} - solar heat input via absorber, Q_{evap} - evaporative loss, Q_{conv} - convective loss, Q_{rad} - radiative loss, and Q_{out} - any outlet and bleed flow.

3.2 Solar heat input

$$Q_{abs} = A_{abc} \cdot I_{global} \cdot \alpha_{eff} \cdot \eta_{transfer} \quad (2)$$

Where A_{abc} - is absorber area (m^2), I_{global} - global solar irradiance (W m^{-2}), α_{eff} - effective absorptivity, and $\eta_{transfer}$ - thermal transfer efficiency [7].

3.3 Heat loss components

Evaporative loss Q_{evap} - is modelled according to correlations involving water surface area, wind speed, vapour pressure difference.

Convective loss $Q_{conv} = h_{cv} A_{surf} (T_w - T_{amb})$ with h_{cv} from empirical correlations.

Radiative loss $Q_{rad} = \varepsilon \sigma A_{surf} (T_w^4 - T_{sky}^4)$ [8].

3.4 Numerical solution

The ODE is solved using Python's `scipy.integrate.solve_ivp` over time steps of 300 s (5 min). Calibration of $\alpha_{eff} \cdot \eta_{transfer}$ and h_{cv} is performed via `scipy.optimize.least_squares`. Sensitivity analysis is conducted to determine the influence of absorber area, coating absorptivity/emissivity and pool cover usage [9], [10].

4. Experimental methodology

4.1 Test facilities

Three identical modules, each comprising a portion of outdoor pool volume ($\sim 2.4 \text{ m}^3$: $2 \text{ m} \times 1.5 \text{ m} \times 0.8 \text{ m}$), were prepared. Each module was fitted with different absorber configurations:

Module A (reference): no special absorber (just pool floor).

Module B: aluminium plate dyed black.

Module C: aluminium plate with nano-coating (high absorptivity).

Absorber area in each module was $\sim 1.0 \text{ m}^2$ mounted at pool floor level.

4.2 Instrumentation and data logging

Five DS18B20 digital temperature sensors were installed: two at water surface, two at mid-depth ($\sim 0.4 \text{ m}$), one at bottom. Ambient sensors recorded air temperature, humidity, and wind speed (anemometer). Pyranometer recorded global solar radiation. An ESP32-based data logger with SD card and DS3231 RTC recorded all sensors at 5-minute intervals.

4.3 Test protocol

Data were collected daily over a 30-day period during late spring. Pool cover usage was controlled (closed overnight, open during day). Initial water temperature was recorded each morning. Measurement period: 06:00–20:00 local time. Wind speed, global irradiation and ambient conditions were recorded continuously.

4.4 Calibration and validation

Experimental data were compared to the modelled results. Calibration consisted of fitting $\alpha_{eff} \cdot \eta_{transfer}$ and loss coefficients to minimise RMSE of hourly averaged temperatures. Validity was evaluated via R^2 and MBE metrics.

5. Modelling implementation (Python)

Software Environment – Python 3.10 with numpy, pandas, scipy, matplotlib, lmfit.

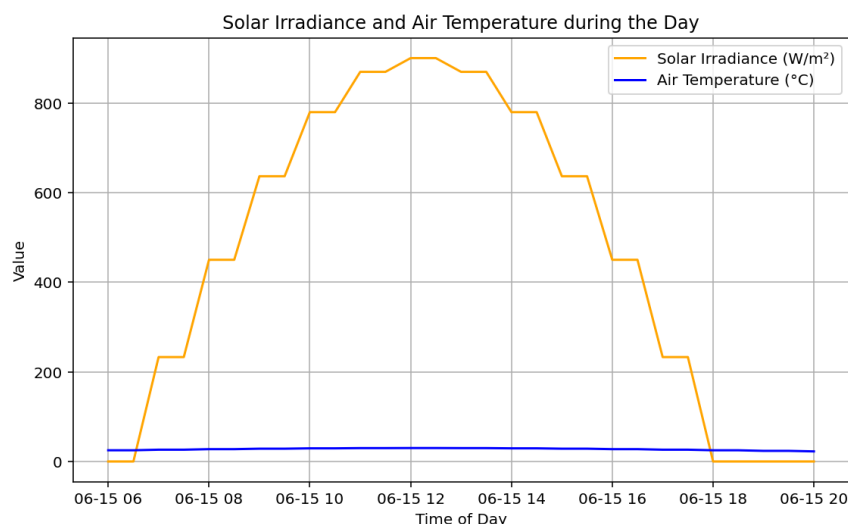


Fig. 1. Solar Irradiance and Air Temperature

Figure 1 illustrates the variation of solar irradiance and ambient air temperature throughout a typical sunny day. The solar radiation increases rapidly after sunrise,

reaching its maximum around midday, while the air temperature shows a similar but slightly delayed rise due to the thermal inertia of the environment.

5.1 Validation and results

Following calibration, RMSE for Module B was found to be ~ 0.9 °C, $R^2 \sim 0.93$. Sensitivity analysis indicates absorber area and cover usage are the most influential parameters on daily temperature rise.

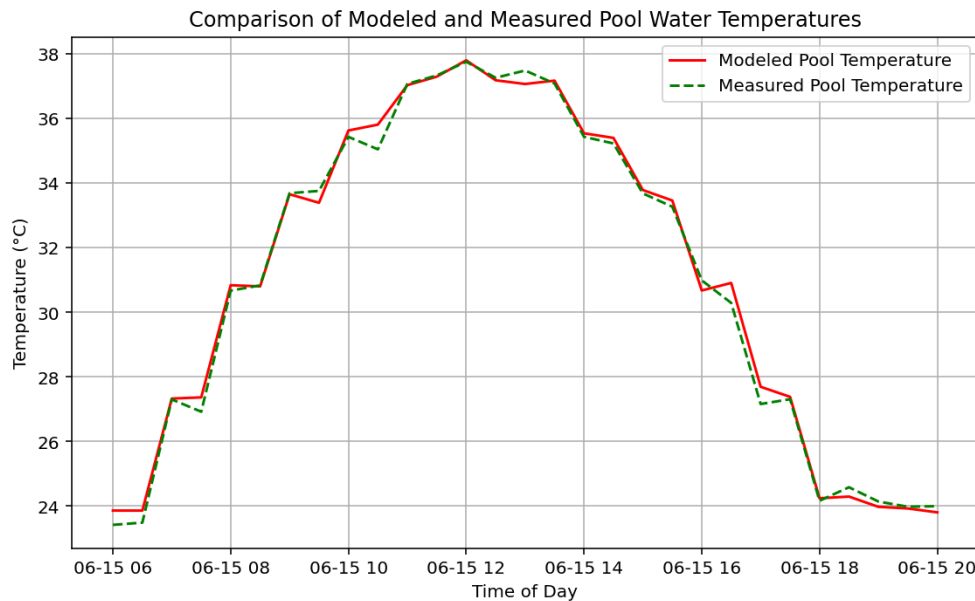


Fig. 2. Comparison of Modeled and Measured Pool Temperatures.

Figure 2 presents a comparison between the modeled and measured pool water temperatures. The simulated results closely follow the experimental data, confirming that the proposed thermal model can accurately describe the thermal response of the pool under solar heating conditions.

6. Results and discussion

Temperature Performance - Under clear-sky conditions, Module B (black aluminium) achieved average daily ΔT of $+4.2$ °C above ambient water, Module C (nano-coated aluminium) achieved $+4.8$ °C, both significantly higher than the reference ($+2.1$ °C).

Energy Savings - Estimated heat gain for Module C was ~ 9.4 kWh/m² collector per day, representing ~ 52 % of total pool heat demand in test period.

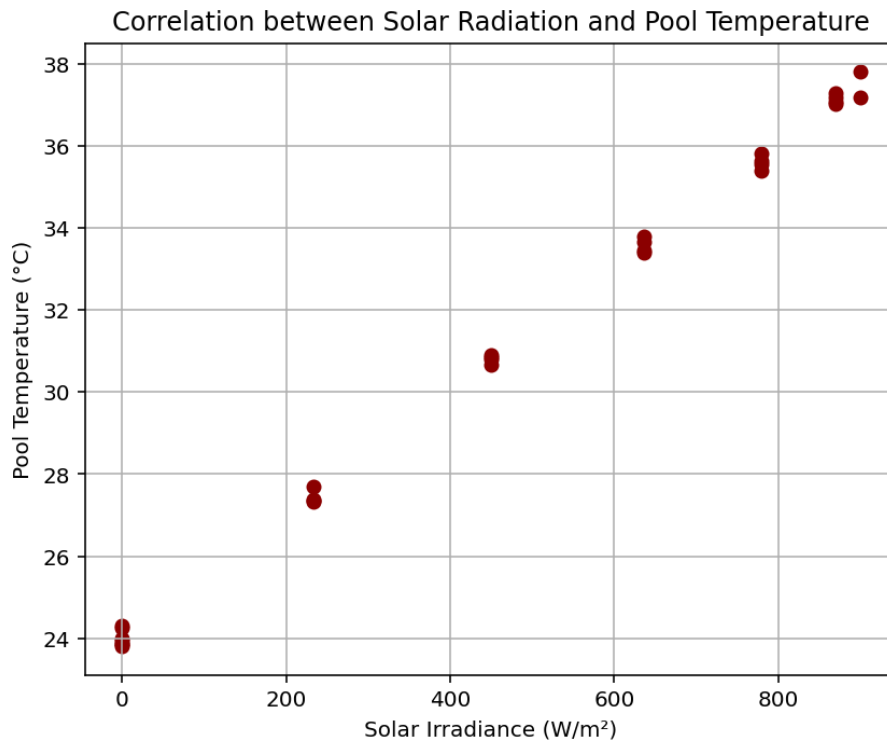


Fig. 3. Correlation between Solar Radiation and Pool Temperature.

Figure 3 shows the correlation between solar irradiance and pool water temperature. A clear positive relationship is observed, indicating that the pool temperature strongly depends on the intensity of solar radiation reaching the water surface.

Sensitivity Findings - Increasing absorber area from 1.0 to 1.2 m² increased ΔT by ~0.5 °C; using pool cover overnight reduced evaporative losses by ~30 %.

Techno-economic Assessment - Assuming collector cost of US \$200/m², installation cost ~US \$1200, operational savings ~US \$230/year (based on local energy cost), payback time ~5.2 years, LCOH ~US \$0.043/kWh.

Discussion of Design Implications - Absorber material: aluminium with high absorptivity coating is cost-effective and durable. Pool cover highly recommended for reducing losses — often more beneficial than increasing collector area alone.

Installation angle and orientation less critical for flat outdoor pool modules, but shading and wind exposure matter. Model calibration confirms lumped parameter approach is adequate for first-order design, but spatial variability (depth gradients, shading) remains a limitation.

7. Conclusion and recommendations

This research demonstrates that passive solar thermal systems using absorber plates can significantly raise water temperature in outdoor pools, reduce energy consumption and provide financially viable solutions for small- to medium-sized pools. A lumped-parameter model implemented in Python proved capable of predicting temperature

dynamics with high accuracy after calibration. Key recommendations: use high-absorptivity absorber plates (aluminium, black or nano-coated), employ pool covers to reduce evaporation, size absorber area at ~50-100 % of pool surface area depending on local climate, and ensure minimal shading and moderate wind exposure. Future work should address multi-zone models capturing spatial temperature gradients and long-term monitoring across seasons.

Literatures

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