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# Swimming pools as heat sinks for air conditioners: Model design and experimental validation for natural thermal behavior of the pool

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ABSTRACT

Swimming pools as thermal sinks for air conditioners could save approximately 40% on peak cooling power and 30% of overall cooling energy, compared to standard residential air conditioning. Heat dissipation from pools in semi-arid climates with large diurnal temperature shifts is such that pool heating and space cooling may occur concurrently; in which case heat rejected from cooling equipment could directly displace pool heating energy, while also improving space cooling efficiency. The performance of such a system relies on the natural temperature regulation of swimming pools governed by evaporative and convective heat exchange with the air, radiative heat exchange with the sky, and conductive heat exchange with the ground. This paper describes and validates a model that uses meteorological data to accurately predict the hourly temperature of a swimming pool to within 1.1 °C maximum error over the period of observation. A thorough review of literature guided our choice of the most appropriate set of equations to describe the natural mass and energy exchange between a swimming pool and the environment. Monitoring of a pool in Davis, CA, was used to confirm the resulting simulations. Comparison of predicted and observed pool temperature for all hours over a 56 day experimental period shows an R-squared relatedness of 0.967.

## 1. Introduction

In California, where all the large electric utilities experience their peak power demand in the summer, space cooling accounts for 29% of the total peak power demand and approximately 40% of the residential peak demand [1]. This occurs in part because the COP for traditional air-cooled vapor-compression cooling equipment diminishes significantly at high outdoor temperatures, such that equipment efficiency can be at its worst when cooling demand is greatest. Thermodynamics for heat pumps dictates that the work required to transfer heat from a cooler source to a warmer sink increases with the temperature difference between the two. In practice, for a vapor-compression system, since heat exchange with the refrigerant at the condenser and evaporator is driven by the temperature differences between the refrigerant and the sink and source respectively, the overall temperature difference experienced by the refrigerant is significantly larger than the temperature difference between the sink and source. For this reason, a large fraction of cooling efficiency research has focused on techniques to reduce heat sink temperatures, and reduce the required temperature differences between the refrigerant and the source and sink. For example, rejecting condenser heat to water instead of air reduces the temperature difference that is needed for adequate heat transfer; air-cooled condensers typically require a refrigerant temperature that is 20 °C higher than condenser inlet air, while exchange with water only needs a 10 °C temperature difference.

The research presented in this paper provides a foundation for the design of cooling systems that reject condenser heat to swimming pools, a strategy that has been deployed successfully in many installations [2,3], but that has not been widely adopted. One reason for the lack of application is the lack of research, documentation and standardization. Our thesis is that a better understanding of the mechanisms that drive performance and savings could inform the development of guidelines for appropriate design of these systems, and could lead to more prevalent adoption, resulting in cost-effective energy and peak demand savings. The savings should come from three mechanisms:

1. Lower sink temperature since pool water is cooler than outdoor air during most cooling periods.
2. Improved heat transfer at the condenser since exchange with water is more effective than exchange with air.
3. Reduction of energy consumption for pool heating.

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## Nomenclature

| | |
|---|---|
| $A_{\mathrm{cond}}$ | surface area of conduction to ground ($\mathrm{m}^2$) |
| $A_s$ | surface area used for shape factor calculations ($\mathrm{m}^2$) |
| $A$ | surface area of pool at air–water interface ($\mathrm{m}^2$) |
| $C_{\mathrm{Bowen}}$ | Bowen coefficient[3] (61.3 Pa/°C) |
| $d_{\mathrm{poolavg}}$ | average pool depth (m) |
| $e_a$ | vapor pressure in ambient air (Pa) |
| $e_s$ | saturation vapor pressure of air at the pool temperature (Pa) |
| $E_{\mathrm{sky}}$ | emissivity of sky (−) |
| $E_w$ | emissivity of water (−) |
| $g$ | acceleration of gravity ($\mathrm{m/s^2}$) |
| $Gr_L$ | Grashof number (−) |
| $\bar{h}$ | average convection coefficient ($\mathrm{W/m^2\ °C}$) |
| $h_{\mathrm{evap}}$ | wind speed function for evaporation ($\mathrm{W/m^2\ Pa}$) |
| $HR$ | humidity ratio (kg/kg) |
| $k_{\mathrm{air}}$ | thermal conductivity of air (W/m °C) |
| $k_{\mathrm{soil}}$ | thermal conductivity of soil (W/m °C) |
| $L$ | average length of pool (m) |
| $L_c$ | characteristic length of pool used for shape factor calculations (m) |
| $\overline{Nu_L}$ | average Nusselt number (−) |
| $O_{\mathrm{sky}}$ | opaque sky cover (tenths) |
| $P$ | perimeter of pool (m) |
| $p_a$ | ambient pressure (Pa) |
| $p_o$ | reference pressure (Pa) |
| $Pr$ | Prandtl number (−) |
| $\dot{q}_{ss}$ | dimensionless conduction heat rate (−) |
| $q_{\mathrm{cond}}$ | conduction heat flux ($\mathrm{W/m^2}$) |
| $q_{\mathrm{conv}}$ | convection heat flux ($\mathrm{W/m^2}$) |
| $q_{\mathrm{evap}}$ | evaporation heat flux ($\mathrm{W/m^2}$) |
| $q_{\mathrm{rad}}$ | radiation heat flux ($\mathrm{W/m^2}$) |
| $Q_{\mathrm{solar}}$ | solar heat gain (W) |
| $R_{\mathrm{Bowen}}$ | Bowen ratio (−) |
| $Ra_L$ | Rayleigh number (−) |
| $S$ | solar input ($\mathrm{W/m^2}$) |
| $T_a$ | ambient air temperature (°C) |
| $T_{\mathrm{dew}}$ | dew point temperature (°C) |
| $T_w$ | swimming pool temperature (°C) |
| $T_{\mathrm{sky}}$ | effective sky temperature (°C) |
| $T_{\mathrm{soil}}$ | soil temperature (°C) |
| $V$ | wind speed (m/s) |
| $\alpha$ | absorptivity of water (−) |
| $\beta_a$ | thermal expansion coefficient of air (1/°C) |
| $\beta_w$ | thermal expansion coefficient of water (1/°C) |
| $\rho$ | density of water ($\mathrm{kg/m^3}$) |
| $\sigma$ | Stefan-Boltzmann constant ($5.67\ \mathrm{E}^{-8}\ \mathrm{W/m^2\ K^4}$) |
| $\nu$ | kinematic viscosity of air ($\mathrm{m^2/s}$) |
| $w$ | average width of pool (m) |

The practical use of condenser heat rejection to swimming pools relies critically on the natural temperature regulation of pools by conductive heat exchange with the ground, convective and evaporative heat exchange with the air, and radiative heat exchange with the sky. The key is to balance heat rejection from the space cooling system with heating demand for the pool, such that pool temperature is maintained in a desirable range. We expect that this balance will be easiest to maintain in climate regions of the western United States, or other semi-arid regions with low ambient humidity and relatively low nighttime temperatures. In these regions, heat dissipation from swimming pools is increased by high evaporation rates in low humidity environments, and by longwave radiative cooling which increases with low ambient humidity and clear skies. Anecdotal evidence suggests that heat dissipation from pools in these climates is such that pool heating is often required to maintain desired water temperature, even when space cooling is required to maintain desired indoor temperature. In this case, heat rejected from cooling equipment could directly displace energy consumed to heat a pool, while concurrently improving the COP of the cooling system.

The objective of this paper is to document and discuss the development of a model to simulate the energy and mass balance of a swimming pool in natural interaction with its local environment; subsequent research will validate the model for simulation of a swimming pool used as a heat sink for vapor-compression air conditioning. Since there is no standardized approach to modeling the thermal behavior of swimming pools, this research draws from the conclusions of many authors to develop a clear and generalized method, and validates model predictions against long-term experimental measurements from a pool in Davis, CA.

## 2. Methodology and results

### 2.1. Model development

An analytical model to determine the heat and mass transfer for a swimming pool was developed to calculate the transient thermal behavior of a pool based on hourly weather data. The model relies on detailed information about the site and the operating characteristics of the pool. Based on meteorological inputs and system conditions, at each hourly time step ($t$), the calculations draw on empirical and theoretical heat transfer correlations to estimate the steady state heat transfer rates for conductive, convective, radiative, and evaporative heat exchange mechanisms. Rates are integrated across the hour, and energy and mass storage terms are calculated to determine the average pool temperature at the beginning of the next hour ($t+1$). Meteorological inputs and system conditions at ($t+1$) are then used to solve for system conditions at the following hour ($t+2$). The following sections describe the basis for calculating heat transfer rates for each mechanism considered in the model.

#### 2.1.1. Insolation

The heat gain ($W$) due to solar radiation is found by multiplying the solar insolation at the pool surface by the absorptivity and area of the pool.

$$Q_{\mathrm{solar}} = S \cdot \alpha \cdot A \tag{1}$$

The concept is simple, but determining the solar insolation and absorptivity are challenging prospects. Insolation at the pool surface is comprised of both direct and diffuse radiation, so when a pool is partly shaded by nearby objects, raw meteorological data for the global horizontal insolation is not representative of actual conditions. To compensate, shading of the pool must be described for each hour by inspection of the site and analysis of solar pathways for the latitude, season, and time period of the simulation. Diffuse insolation is used as the solar input for shaded periods and global

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[3] The Bowen Coefficient is 6.13 Pa/°C for the case when evaporation from a water surface does not significantly impact absolute humidity of the air.