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The Prediction of Thermal Performance for Outdoor Swimming Pools

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ABSTRACT

Empirical methods and industrial guidelines are conventionally used for arriving at heating needs of outdoor community swimming pools which seldom account for local climatic conditions. This paper presents a comprehensive model to estimate the water temperature of an outdoor swimming pool and then to estimate heating-plant size. The important feature of the present model is that all comprehensible modes of heat and mass transfer and topographic conditions are incorporated. The notables are the heat and mass transfer to/from swimming pools through free and forced convection, radiative cooling to the sky, and climatic changes such as cloud cover and rainfall. The ambient weather conditions and solar contributions are also found to be significant contributors. The consequent predictions of pool-water temperature are evaluated vis-à-vis measurements from an Olympic size open air swimming pool in Perth, Australia. Based on a comparison among some models in the literature, it is found that the present model is able to replicate the measured data to within ±0.5°C for nearly 68% of the results over a three year time frame. The subsequent heating-capacity calculations are found to be satisfied in 82% of the measured values to within ±25 kW.

1. INTRODUCTION

Swimming pools are the places where energy, water, and sustainability have to be intricately balanced against health, entertainment, and recreation. The latest trends show that many governmental agencies try to make community swimming pools available throughout the year for users. As stipulated by Fédération Internationale de Natation (FINA), the water inflow-outflow for a 50-m Olympic size pool should be 220-250 m^3/h and the temperature of the swimming pool maintained in the range of 25-28 °C [1]. Unfortunately, it is difficult to control the temperature of the pool to within range during winter. In the southern region of Australia, the conflation of rainy season and winter causes problems for most of the recreational aquatic centres due to many cold fronts sweeping the continent. These occurrences negatively impact several outdoor Olympic size pools which are well patronised. According to a CFD based evaporation calculation scheme, even for an indoor swimming pool facility, it was estimated that evaporation and ventilation contributed to about 60% of the total energy requirements [2]. Therefore, it is important to predict the energy consumption due to evaporative heat loss properly. Due to the evaporation problem, another environmental facet, namely potable water consumption, is highly important for maintaining the pool-water levels. It was concluded that the evaporation of water contributes 60% to heating inventories in the Italian capital territory among various enumerated contributors [3]. The fact that 16 million m^3 of treated potable water is consumed in each pool per year must also be of great concern.

In the abovementioned background, appropriately sized heating plants are vital to maintain the water of an outdoor community swimming pool at a preferred temperature, especially in winter. The required thermal energy is often provided by a gas fired water heating system. To reduce greenhouse gas emissions, several other options can be used to provide this kind of heating, with geothermal water aquifers being one of them [4, 5]. The Western Australia region has a number of expansive shallow geothermal aquifers. The source for pool heating is warm groundwater (~46°C) at ~1 km depth. The spent groundwater is pumped to a shallower depth aquifer using a pair of bore holes that are separated by an appropriate distance to prevent any thermal breakthrough [6, 7]. Geothermal systems are preferred more than others in Australia, despite their capital costs, as they do not require a large land footprint when compared to solar energy heating systems. There are other sources of energy being explored in the past, such as ground source heat pumps [8, 9] and solar energy [10, 11].

Ideally, renewable sources of energy should be the only means for heating large pools. However, it is often the case that during winters these sources of energy have to be supplemented by fossil-fuel fired boilers. This also arises in part because of the uncertainties in estimating the heating capacity of outdoor pools when they are exposed to gales and clear sky, which are typical in Australia.

The methods of heating-capacity sizing for the outdoor pools have been, to date, mainly empirical [12-15] and seldom location specific. Moreover, the lack of well documented ambient conditions could lead to significant inaccuracies in the application of these methods outside the specific geographical areas. There is no standard method for calculating losses in a pool, specifically in quantifying evaporation losses [16]. It is therefore necessary to generate a model that is capable of delivering accurate values for calculating heat loss due to evaporation. Above all, the model should be applicable to solve evaporation losses in both outdoor and indoor pools. Over or under-sizing the heating system is most likely going to happen without a fine-tuned thermal model, that can predict the water temperature of an outdoor pool. This surely will have an impact, not only on the users' thermal comfort, but also on commercial aspects and the control of pool-water temperature.

The present development (henceforth referred to as the UWA model) augments the capabilities of those in vogue [11-13, 15]. The addenda are improved estimation of heat transfer due to natural and forced convection evaporation and heat transfer, radiation between the pool and its surroundings, solar inputs, cloud and rainfall. The results from such calculations are compared with experimental data gathered over 36 months (March 2016 to March 2019 with a hiatus due to the refurbishment of the pool heating system from March to September 2018) from an Olympic sized swimming pool which is heated using geothermal water [17]. Whilst outdoor swimming pools are the focus of the current analysis, other contained water systems that require a stable water temperature, such as aquaculture, can also make use of these findings [18]. This paper is an extension of an earlier one [19] with the proviso that the comparative analysis has been refined and revised assessment is now made based on more expansive data that covers more winters.

2. HEAT TRANSFER AND EVAPORATION MODELLING

The basic equations of the thermal model remain the same as before [19] and are reproduced hereunder for the sake of completeness.

$$Q_{pool} = Q_{evap} + Q_{conv} + Q_{rad} + Q_{refill} - Q_{solar} \tag{1}$$

$$Q_{evap} = \left(Q_{evap,\,fc}^{7/2} + Q_{evap,nc}^{7/2} \right)^{7/2} \tag{2}$$

$$Q_{conv} = \left(Q_{conv,\,fc}^{7/2} + Q_{conv,nc}^{7/2} \right)^{7/2} \tag{3}$$

$$Q_{rad} = \frac{\sigma \varepsilon_w A \left(T_w^4 - T_{sky}^4 \right)\left(1 - F_{w-structure}\right)}{\left(1-\varepsilon_w\right)\left(1 - F_{w-structure}\right) + \varepsilon_w} \tag{4}$$

$$Q_{refill} = \dot{n}_{evap} c_{p,w} \left(t_w - t_{refill} \right) \tag{5}$$

$$Q_{solar} = \alpha_{pool} A \left(E_{beam} + E_{diffuse} \right) C_{cloud\ effect} \tag{6}$$

The heat loss due to conduction is extremely minor and can be neglected if it is compared to other modes [3]; it is usually smaller than 1% of the total heat loss of the pool [13-14]. Figure 1 shows the present Olympic-sized pool which is set belowground and has a wet deck.

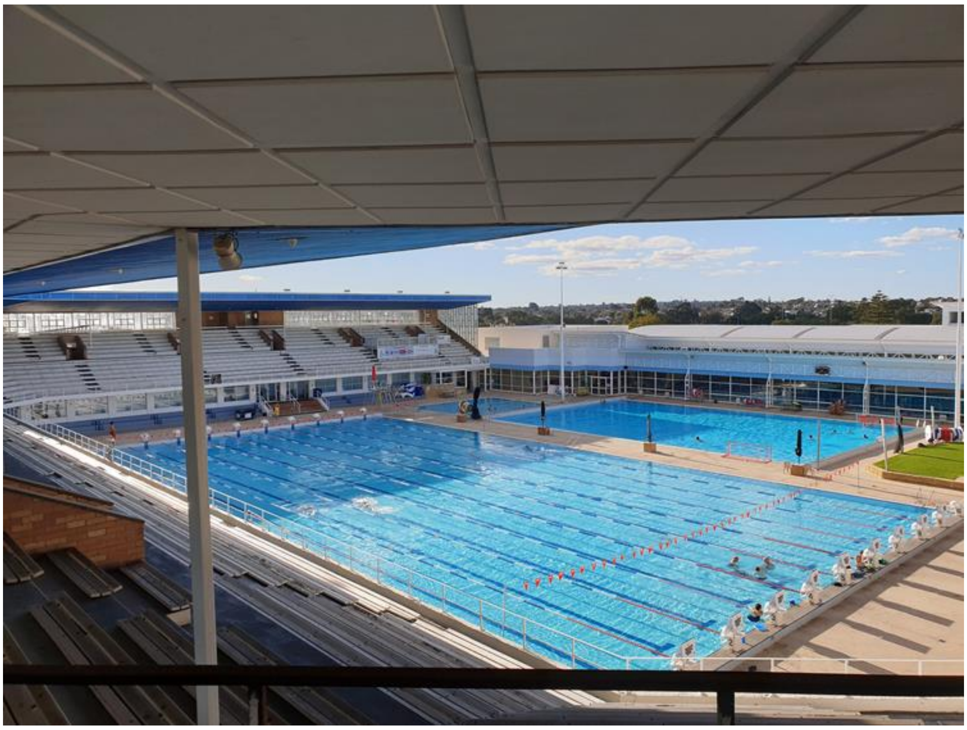

Figure 1: The 50-m 10 lane outdoor swimming pool of Beatty Park with depths from 1.2-1.8 m [17]. Side view

2.1 Evaporation (Q_{evap})

The improvement as envisaged in the UWA model is the extensive treatment of the evaporation heat transfer due to forced and free convection heat transfer [19]. Significant contributions are made by free convection heat and mass transfer as well as due to a synergetic contribution from the forced convection heat and mass transfer which is represented in eqs (2 and 3).

2.1.1 Heat transfer for forced convection evaporation

The UWA model accords considerable weightage to the surroundings of the pool and the wind flow direction to calculate the forced convection heat transfer as follows.

For the angle incidence of θ = 22.5° or 45°,

$$Q_{evap,\,fc} = 2c_m\left[W\sin(\theta)\right]^{9/5} + d_m W^{4/5}\left[L - W\tan(\theta)\right]\cos^{1/5}(\theta) \tag{7}$$

for θ = 67.5°,

$$Q_{evap,\,fc} = c_m\left[L\cos(\theta)\right]^{9/5} + d_m W L^{4/5}\left[1 - 1/\tan(\theta)\right]\sin^{1/5}(\theta) \tag{8}$$

where

$$c_m = \frac{0.37}{9}\left(\rho_{w,s} - \phi\rho_{w,\infty}\right)D_{AB}\,Sc^{1/3}Re^{4/5}\left[\frac{2}{\sin(2\theta)}\right]^{4/5} h_{fg} \tag{9}$$

$$d_m = 0.037\left(\rho_{w,s} - \phi\rho_{w,\infty}\right)D_{AB}\,Sc^{1/3}Re^{4/5}h_{fg} \tag{10}$$

2.1.2 Heat transfer for free convection evaporation

The UWA model calculates the free convection heat transfer by first evaluating the free convection mass transfer as follows.

$$\dot{n}_{w,s} = h_{evap,nc}A\left(\rho_{w,s} - \phi\rho_{w,\infty}\right) \tag{11}$$

This is then used to evaluate the free convection heat transfer as follows.

$$Q_{evap,nc} = \dot{n}_{w,s}h_{fg} \tag{12}$$

2.2 Convection heat transfer (Q_{conv})

The convection heat transfer also has both forced and free convection components. These are combined, as shown in eq (3) for the same reasons as stated in section 2.1.

2.2.1 Heat transfer for forced convection

The treatment of forced convection heat transfer follows an analogous approach as in eqs. (7 to 10). The subscript *m* changes to *fc* and *Sc* is replaced by *Pr* and $(\rho_{w,s}-\phi\rho_{w,\infty})D_{AB}$ with $(t_w-t_\infty)k_{a,f}$.

2.2.2 Heat transfer for free convection

The free convection heat transfer is evaluated as follows.

$$Q_{nc} = h_{nc}A\left(t_w - t_\infty\right) \tag{13}$$

The radiative heat transfer was also given a detailed treatment in [19] which is not repeated here.

3. THE DESCRIPTION OF EXPERIMENTAL SWIMMING POOL

The experimental data pertains to a 50-m outdoor swimming pool at the Beatty Park Leisure Centre in Perth, Western Australia. There is no pool cover being used for this swimming pool. In terms of process control, when the pool-water temperature drops below the set point, the geothermal pool water heating system is activated. There is also a conventional boiler that acts as a heat inventory supplement. The pumps are set at a flow rate of 8.5 L/s and use an on-off control strategy to maintain the pool-water temperature. Other relevant data for the pool is shown in Table 1. During the period from March 2016 to March 2019, all the required parameters were recorded at 30-minute intervals. The pool was not operational from March to September 2018 due to a heating system refurbishment. The temperature measurements were made with thermistors which have an uncertainty of 0.2°C.

Table 1. The Parameters of the Beatty Park Swimming Pool

Length	50 m
Width	25.5 m
Average depth	1.5 m
Set water temperature of the pool	26.5 °C
Design flowrate of pool pump	8.5 L/s
Orientation of the pool	45° (0° is E-W)
Latitude	-31.9°S
Longitude	115.85°E
Height above MSL	24 m
Total volume	1912 m^3
Annual rainfall	786 mm

3.1 Weather Data

The meteorological data was collected from the Bureau of Meteorology (BOM) Perth Metro weather station which is the nearest to the Beatty Park Leisure Centre.

4. RESULTS AND DISCUSSION

4.1 The Comparison of Temperature Prediction

The histograms in Figure 2 show the temperature variations of the recorded open pool temperature against the UWA model and other models. The frequency covers all the recorded data from March 2016 to March 2019 stretching over 5000 data points. The UWA model can be seen to be the most consistent, with 68% of all the data being within ± 0.5 °C of the measured temperature. The Wooley model (tile C in Figure 2) [13] produced 61% of its results to within the same ± 0.5 °C. There were about 23 patrons per hour on an average in the pool during winter months; the thermal effect of these users has not been actively incorporated into any of the models as it is trivial compared to other heat quantities.

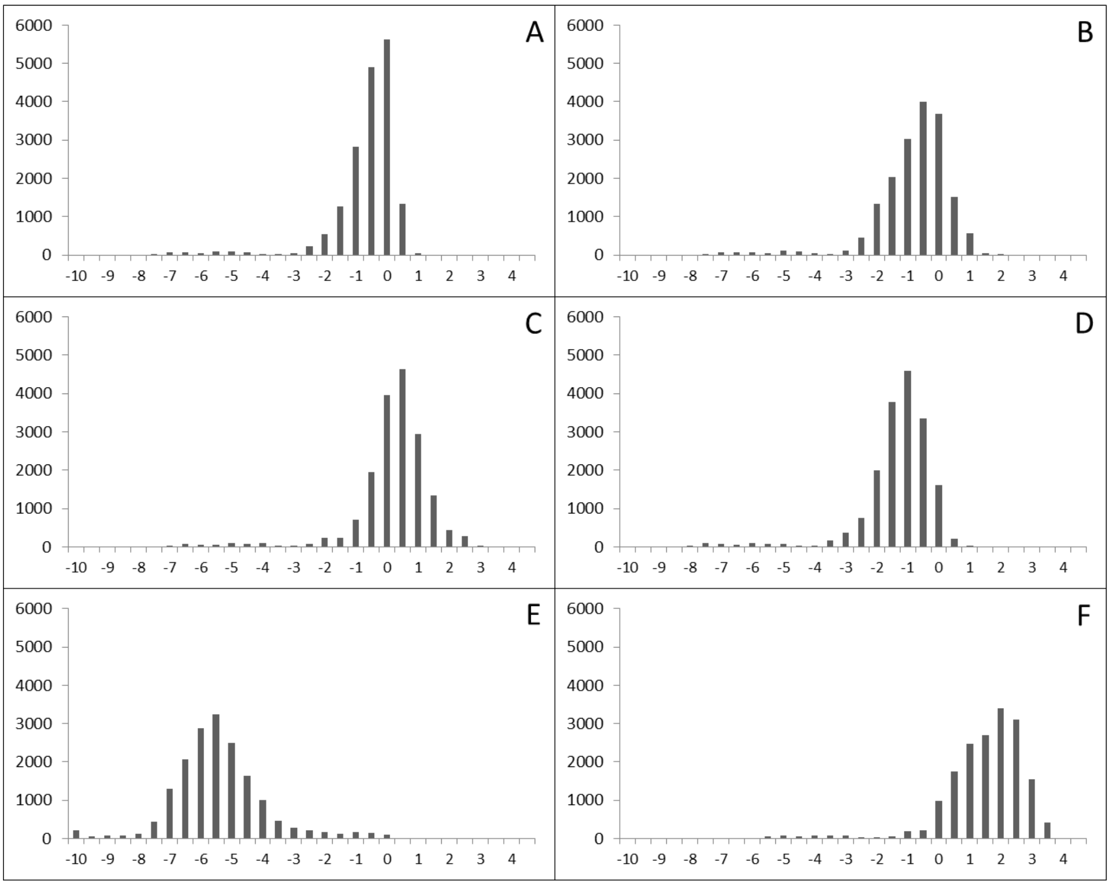

Figure 2: The frequency distribution of various models against measured deviations from pool water surface temperatures. The abscissa is the variation in temperature in ˚C, and the ordinate is the frequency in all figures. Legend: A: UWA model, B: [12]; C: [13]; D: [15]; E: [20]; F: [21]

The AS3634 model [21] consistently over-predicts the pool temperature with an average over prediction of 1.48 °C. If the AS3634 model was used in the planning of a new swimming pool, it could result in the under sizing of the pool heating plant. Conversely, the ASHRAE model [20] consistently under predicts the temperature with an average under prediction of -5.42 °C. This will result in an over-sizing of the pool heating plant.

Table 2 compares the various models in terms of the percentage differences between the modelled and measured pool water surface temperatures to within ±0.5 °C of the measured temperature. These differences mainly stem from the different treatment of evaporation by the various models.

Table 2. The prediction of the water surface temperature of the pool to within ±0.5 °C of the measured heating capacity by the various models.

Model	%
UWA	68
Woolley *et al*. [13]	61
McMillan [12]	53
Richter [15]	30
AS3634 [21]	17
ASHRAE [20]	1

4.2 The Comparison of Heating Capacity Predictions

The predicted temperature of all the six models are used to predict the geothermal heating requirement. Figure 3 shows the differences between the measured and predicted heating demands for the various models, throughout the entire period of experimentation, in the form of histograms. The heating capacity deviation distribution from the UWA model can be seen in Figure 3 and shows a high frequency around zero deviation. The comparison of the models with the experimental heating capacities can only be conducted when the geothermal pump is on. This is the reason for having fewer data sets here than in Figure 2. A comparative assessment of all the models is given in Table 3 in terms of the percentage of their results that have a difference between modelled and experimental heating capacities to within ±25 kW. The difference between the models stems from the variability in the treatment of evaporation by the various models.

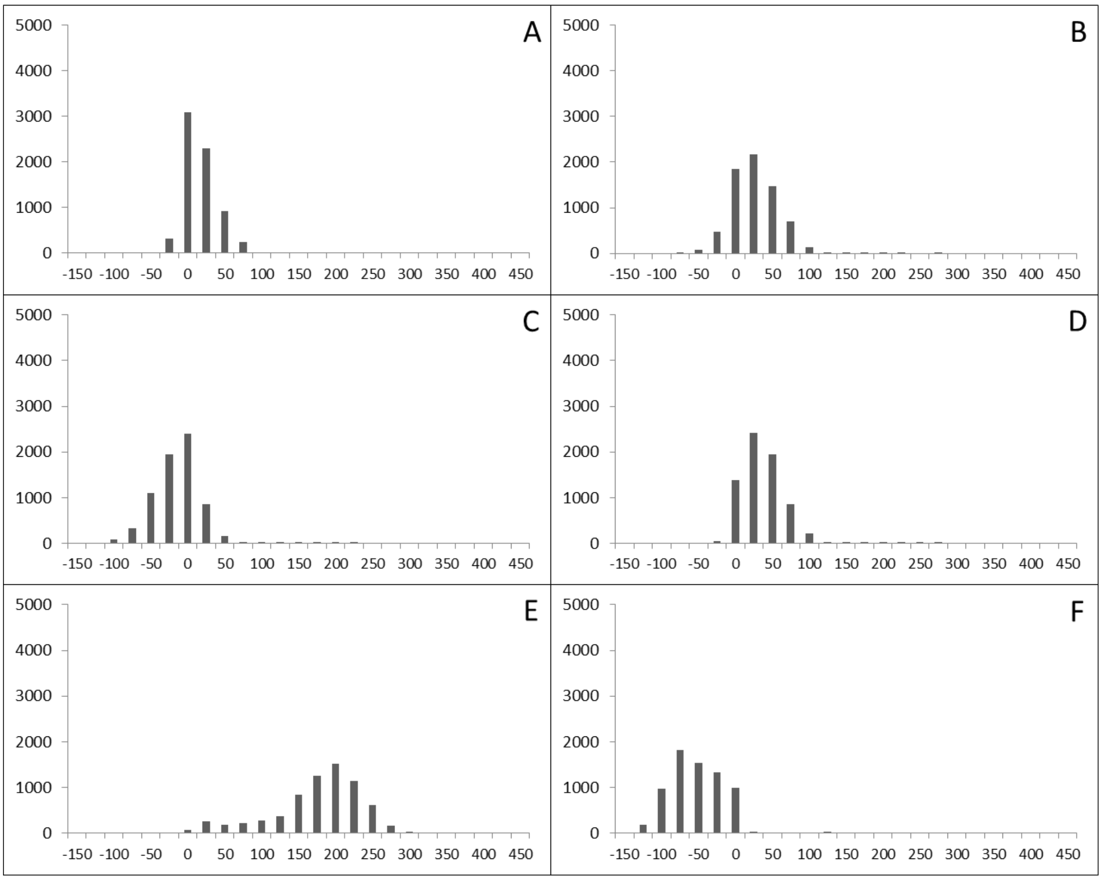

Figure 3: The frequency distribution between measured heating capacity demands and the various models. The abscissa is the variation between the measured and calculated heating demands (kW), and the ordinate is the frequency in all the figures. Legend: A: UWA model, B: [12]; C: [13]; D: [15]; E: [20]; F: [21]

Table 3. The comparison of the predictive accuracy of the various models to within ±25 kW of the measured heating capacity.

Model	%
UWA	82
Woolley *et al.* [13]	75
McMillan [12]	65
Richter [15]	55
AS3634 [21]	34
ASHRAE [20]	6

5. CONCLUSIONS

A model was developed to predict the temperature of water and the heating plant capacity of outdoor swimming pools. The measured data of a swimming pool located at the Beatty Park Leisure Centre in Perth, Australia covering a period of three winters were used to evaluate the model. 68% of the predicted temperatures were within ±0.5°C of the measured values, while 82% of the heating capacities estimates were within ±25 kW of the measured heating inputs. The model has been benchmarked against other models currently in use.

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NOMENCLATURE

A	pool surface area (m^2)
$C_{cloud\ effect}$	a scaling effect that occurs due to shading
c_p	specific heat (kJ/kg·K)
D_{AB}	coefficient of binary diffusion for water and air at 1 atm (m^2/s)
E	solar flux
$F_{w\text{-}structure}$	view factor between water and surrounding structure
h_{fg}	heat of vaporisation of water at pool temperature (kJ/kg)
h	heat transfer coefficient (W/m^2·K)
L	length of swimming pool (m)
$\dot{n}$	the rate of mass transfer (kg/s)
Pr	Prandtl number
p	pressure (kPa)
Q	thermal energy transfer rate (kW)
Re	Reynolds number
Sc	Schmidt number
T	temperature (K)
t	temperature (°C)
U	wind speed (m/s)
W	width of swimming pool (m)
Greek symbols	
α	absorptivity of the pool
ε_w	emissivity of water surface
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2·K^4)
ϕ	relative humidity (%)
θ	angle of incidence of wind
Subscripts	
a	air
$evap$	evaporation
$conv$	convection
fc	forced convection
nc	natural convection
rad	radiation
$refill$	refill water
s	pool water and air interface
w	water
∞	free stream air

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