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Sensitivity analysis of an outdoor swimming pool under dynamic conditions

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Abstract

Public swimming pools have an important energy consumption and are rarely optimized. One way to do so is to develop a model able to represent the swimming pool behaviour (water temperature and energy consumption) whatever the climatic conditions. The evaluation of thermal losses is done in this work thanks to the presented model and to measurements (ambient air and pool's temperature, relative humidity, direction and velocity of wind, global solar irradiation) performed on a public outdoor swimming pool situated in La Reunion, a French overseas department located in the Indian Ocean close to Mauritius). Each contribution to the decrease of water's temperature is clearly identified and represented, leading to quite accurate comparisons between simulated results and tests for 4 different nights.

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Keywords: evaporation; dynamic simulation; long wave radiation losses; thermal modelling; swimming pool

1. Introduction

Public swimming pools have an important energy consumption (heating, dehumidification and sanitary hot water): around 2800 kWh per square meter of water surface but are rarely optimized [1]. The long-term objective of the current work is to find the best daily heating strategy to apply to a swimming pool energy system by simulating its dynamic evolution. The ability to attain the target depends on the quality of the predictive model taking into

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account all the significant physical phenomena, the weather, the geometry of the place and the users' behavior. Many complex and coupled heat transfer enter into account in the system.

The objective aimed in the paper is to identify the most significant factors having an influence on both the energy losses and on the dynamic evolution of the swimming pool water's temperature. A first part of this paper will present the global modelling of an outdoor swimming pool. A second will describe the example of a public swimming pool situated in La Reunion. The model is compared to the experiments in a third part.

Nomenclature

A	surface of the water, m²
Cp/ C_v	heat capacity, J kg^{-1} K^{-1}
G	global radiation at the water level, J m^{-2}
h	heat exchange, J m^{-2} K^{-1} or J m^{-2} Pa^{-1}
H	enthalpy specific J kg^{-1}
k	conductivity W m^{-1} K^{-1}
L	energy given by swimmers J
$\dot{m}$	mass flow kg s^{-1}
Num	number of swimmers
P	pressure Pa
$\dot{Q}$	heat flow W
t	time s
T	temperature K
U	internal energy J
v	wind velocity m s^{-1}
V	volume m^3
α	absorption coefficient of the water
ε	emissivity
ρ	density kg m^{-3}
σ	Stephan Boltzmann constant $5.6704 \cdot 10^{(-8)}$ W m^{-2} K^{-4}

Relative to

a	ambiant
atm	atmosphere
conv	convection
e	enter
evap	evaporation
heat	heating
o	out
rad	radiative
sat	saturation
sol	solar
v	vapour
w	water

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2. Dynamic modelling of a swimming pool

A lot of swimming pools models can be found in the literature [2], [3], [4], [5] and using the energy and mass balances, a dynamic model has been built [6]. In parallel, an outdoor swimming pool situated in La Reunion (a French overseas department located in the Indian Ocean close to Mauritius), has been equipped in order to collect data (ambient air and pool's temperature, relative humidity, direction and intensity of wind, global solar irradiation).

Figure 1 presents schematically all the fluxes (mass and heat) involved in a swimming pool:

- Heat losses: evaporation, convection between water and ambient air, conduction between water and the soil through the walls, long waves radiations;
- Heat gain from the solar radiation;
- Activity: number of people in the water and human behavior (sport or pleasure, regular use of the thermic cover protection…).

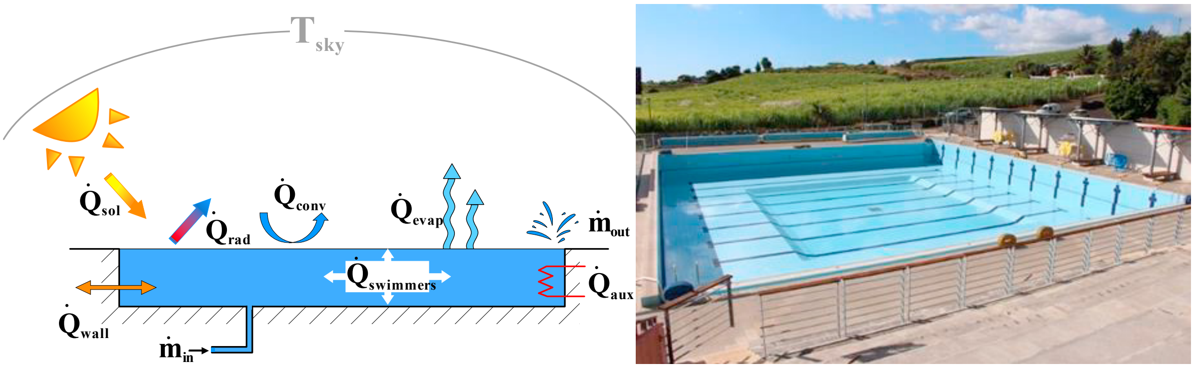

Figure 1 : Swimming pool scheme and main phenomenon having an influence on energy and mass balance and experimented swimming pool

The energy conservation equation gives:

$$\frac{dU_w}{dt} = \rho_w.V.C_v.\frac{dT_w}{dt} = \dot{Q}_{sol} + \dot{Q}_{rad} + \dot{Q}_{evap} + \dot{Q}_{conv} + \dot{Q}_{wall} + \dot{Q}_{swimmers} + \dot{Q}_{aux} + \dot{m}_{in}\,\mathrm{h}_{in} - \dot{m}_{out}.\mathrm{h}_{out} \quad (1)$$

Where general expression for each energy flow model in presented in the table 1.

Table 1 : heat transfer models interacting between the pool and the surroundings.

Flux (W)	Equations	Sign	Refs
Global Radiation	$\dot{Q}_{sol} = \alpha.G.A$	>0	[5], [7]
Longwave radiation losses	$\dot{Q}_{rad} = \varepsilon_w.\sigma.\left(T_{sky}^{\ 4} - T_w^{\ 4}\right).A$	<0	[4], [8]
Convection losses	$\dot{Q}_{conv} = h_{conv}.\left(T_a - T_w\right).A$	<0	[9], [10]
Evaporation losses	$\dot{Q}_{evap} = h_{evap}.\left(P_{sat}(T_w) - P_v\right).A$	<0	[11]
Conduction losses	$\dot{Q}_{wall} = k.A_{wall}.\left(T_{soil} - T_w\right)$	<0	[12]
Swimmers heat	$\dot{Q}_{swimmers} = Num.L_{swimmers}$	>0	
Heating	Depend of heating system (solar, heat pump…)	>0	[2]

In a previous work [13], focus has been made on the evaporation process and among the 20 models tested, the one from Shah [11] revealed the most accurate, mainly because it takes into account the influence of the air flow regime. Nevertheless, its form remains similar to the one of table 1. The mass of water evaporated represents also the district water that has to be added to the pool ($\dot{m}_{in}$) so as to maintain a constant level.

Concerning long wave radiation losses, the model proposed by Walton *et al.* [8] is generally mentioned and has been chosen here. The evaluation of T_{sky} in governed by ambient temperature, humidity and nebulosity.

Convection models are relatively similar to those concerning evaporation and the one proposed by Padet [9] has the advantage to take into account laminar and turbulent flows.

Conduction losses through the walls and the bottom of the swimming pool are generally very low and are often neglected [14]. The model proposed by Woolley *et al.* [12] considers a form factor adapted to the swimming pool and has been chosen in our case.

3. Experimental setup

The swimming pool experimented is located on the site of Vue-Belle at Saint-Paul (La Reunion, longitude: 55.275441° and latitude:-21.077502) at a height of 520 m. The dimensions of this overflowing swimming pool are approximately 25*25*2.3 and the set temperature is 28°C. The water volume is about 1500 m^3.

A weather station is also on the same site at a height of 3 m and measures the ambient temperature, the relative humidity, the Global Horizontal Irradiation, the wind velocity and direction and the rainfall quantity with a step time of 15 min.

As mentioned before, modeling and simuling the dynamic behaviour of the swimming pool is complex and we decided to focus mainly in this paper on losses, in order to overcome heat gains which could interfere with the global temperature evolution. This is the reason why, only data obtained when the swimming pool is not heated and during nights without cover are presented. Table 4 summarises the mean experimental conditions reached during the hot season, more precisely in end of November, beginning and end of January. These 4 cases have been chosen among a great quantity of data in order to represent the discrepancy of results.

Table 2 : Experimentation date and weather mean values

	case 1	**case 2**	**case 3**	**case 4**
Beginning date and hour	24/11/2016 20:00	25/11/2016 21:30	06/01/2017 19:00	29/01/2017 19:00
End date and hour	25/11/2016 05:00	26/11/2016 05:00	07/01/2017 05:00	30/01/2017 05:30
Initial water temperature (°C)	26.14	26.03	29.83	27.7
Ambient Temperature (°C)	19.65	19.24	21.59	21.94
Relative Humidity (%)	82.64	78.82	66.41	80.86
Wind speed (m/s)	0.90	1.14	1.49	0.94

4. Simulation and experimental comparison.

Most of the parameters used in the simulation were those mentioned in the different models presented above. All the thermal-physical properties (heat capacity, density, viscosity, emissivity, etc) have been taken constant over the variation conditions. The global model is solved thanks to a RK4 method with a step type of 1 min and experimental swimming pool temperature is measured every 3 min.

Figure 1Figure 2 presents the comparison of experimental and simulated water temperature of the swimming pool. Case 1 and 2 have a similar evolution since data are obtained in quite the same conditions in terms of initial water temperature and ambient climatic conditions (temperature, relative humidity and wind velocity). Except the fact that the initial temperature is different, Case 4 behaves about the same as previous cases mainly because ambient conditions are similar (wind velocity and relative humidity) despite a higher ambient temperature. The difference of temperature with water having about the same order of magnitude, the corresponding losses are also in the same range. Case 3 is much more different than the others, particularly concerning the slope of the line which is more important and corresponds to higher thermal losses. The origin of this behaviour is due to two different factors; the increase in wind velocity which contributes both to convection and evaporation and a lower ambient relative humidity leading to higher evaporation losses.

Thanks to the different models presented above and to these different experiments, the model reveal quite accurate, even when submitted to different ambient conditions and a more detailed analysis has been carried out. The corresponding results can be seen in figure 4 where each contribution to the total losses are detailed. Since each experiments do not lasts the same time, the energy fluxes have been integrated over the total duration in each case and divided by the duration itself so as to be able to compare them.

As mentioned earlier, the higher losses are obtained in the case n°3, mainly because of a higher evaporation rate. Globally, the radiation loss intensity remains rather the same whatever the case, probably because the temperature difference between the swimming pool and the sky during the nights does not change significantly. The third contribution in magnitude is due to convection but reveals very low in all these cases and is certainly due to a wind velocity of about 1 $m.s^{-1}$ only, leading to low heat transfer coefficients. In the end, all the other contributions (conduction and added district water to fill in the swimming pool) are representing approximately 1 or 2 % of the whole losses as generally noted in the literature [12].

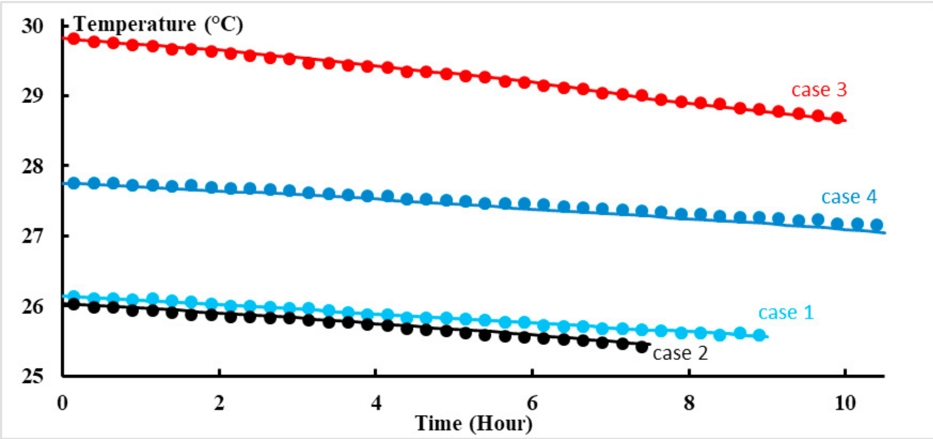

Figure 2 : Evolution of the experimental (dots) and simulated (lines) water temperature of the swimming pool over time.

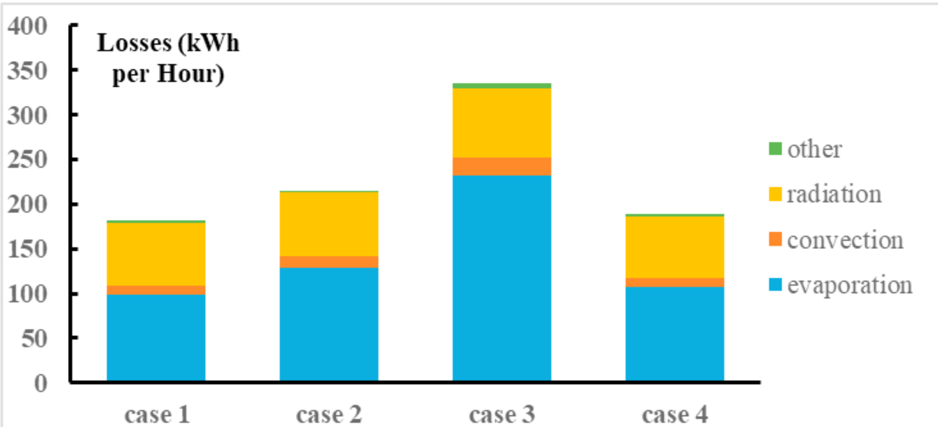

Figure 3 : Analysis of the origin of energy losses for each investigated case.

5. Conclusion

In this work, comparison has been made between experiments and simulation of a swimming pool under dynamic conditions. To override the influence of the heater (a heat pump in this case) and of solar gains on the time dependent behavior of water's temperature, specific tests have been made during summer night so as to properly evaluate heat losses. Among the various contributions and in accordance with the literature, the identified most important one is evaporation, which accounts between 55 and 70 %, depending on the 4 different tested cases. It has been demonstrated that wind velocity and relative humidity in the ambient air have the most important influence on this specific phenomenon. The second one, also in accordance with the literature is the long wave radiation from the swimming pool to the surrounding areas and in particular to the sky (20 to 40 %). In the 4 investigated cases, the analysis led to an almost identical value whatever the conditions. The third contribution to total losses is convection and accounts for less than 10 % mainly because of low values of wind velocity during the experiments. The last part represents between 1 and 2 % and corresponds to losses through the walls and also to the input of district water that offsets evaporation.

Simulations and experiments are in very good agreement and allow to think that these losses are correctly identified and represented by the model. The next step consists in extending this work to days in order to take into account solar gains and also to encounter different climatic conditions to definitely validate the work. The challenge will be later to integrate the heater and to compare energy consumptions before trying to reduce them by applying the most suitable and efficient heating strategy.

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