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Experimental test for the estimation of the evaporation rate in indoor swimming pools: Validation of a new CFD-based simulation methodology

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ABSTRACT

The aim of this work is to present an experimental procedure at laboratory scale that was developed to validate a new CFD-based methodology for the estimation of water evaporation rate in indoor swimming pools, under a wide range of convective flow conditions (36 experiments) and focussing on the most common operation conditions of these facilities: low air mean velocities (0.08–0.24 m/s), and water and air temperatures in the ranges 24-28 °C and 26-30 °C, respectively. One of the main hypotheses of the simulation methodology set a free slip wall condition (no shear stress) at the air-water interface, based on the fact that the dynamic boundary layer depth will be smaller than the thickness of the thermal and humidity boundary layers in this kind of flows. The comparison between simulated and experimental results show that the modelling strategy proposed is a promising tool, with average relative errors of 9% for the typical mixed convection flows in indoor swimming pools.

1. Introduction

Water evaporation in buildings with indoor swimming pools is of great interest for building energy analysis. According to some studies, energy consumption of units used both for air dehumidification and conditioning of swimming pool water, can amount to 60% of the total energy consumption from the rest of heating and cooling systems [1].

The amount of water evaporated is calculated from the so-called evaporation rate, that is usually expressed in terms of mass flow per unit surface of pool. A wide range of correlations are available in the literature for predicting water evaporation rates on free water surfaces. In this regard, a summary of these correlations can be found at [2] [3], and [4]. These correlations can be classified according to the type of convection regime, natural or forced. In forced convection flows, correlations show that evaporation rate depends on both the difference between the partial pressures of vapour saturated at water temperature and the partial pressure of water vapour at air temperature and air velocity. However, under natural convection conditions, it depends on the difference of vapour partial pressures and the difference of air densities.

The most recent and noteworthy studies related to water evaporation in indoor swimming pools may be classified into two groups: tests in real swimming pools and laboratory scale tests. These studies have been listed and described briefly in Table 1.

The study of Hyldgård [5] provides experimental measures in a real indoor swimming pool, which are suitable for the modelling and experimental validation of models of evaporation rate estimation. The test is developed in steady state, with very low average velocities (smaller than 0.15 m/s). Temperature and velocity are measured by K-type thermocouples and a hot wire anemometer, respectively. The amount of evaporated water is measured by using a device developed by the author that is based on the measurement of water level in the pool, with an accuracy of 0.02 mm (0.14 l approximately).

The work of Smith et al. [6] is developed in a large indoor swimming pool and evaporation rate measurements are made from changes in water level and from steam consumption in the pool water heater. Authors make a comparison between the values of evaporation rates estimated from the correlations published by ASHRAE with their experimental data, yielding errors up to 32%. Therefore, they recommend the readjustment of the correlation coefficients for a better estimation.

Unlike tests in real swimming pools, scale laboratory tests are more numerous. In this regard, Pauken [7] carries out an interesting study in a wind tunnel with a large size of the evaporation pan and low velocities of the air stream. The water mass loss in the evaporation pan was determined by connecting it to a smaller pan that rested on an electronic scale through a siphon tube. In this study, the author focusses his attention on the (free or forced) convection conditions for which classical correlations are used. Thus, he concludes that these correlations lead to inconsistencies in evaporation rate predictions, probably because they do not adequately describe evaporation regimes for which

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Nomenclature

A	area, m^2
dA	differential area, m^2
D	mass diffusivity, m^2/s
E	evaporation rate, kg/(m^{2}s)
Gr	Grashof number
H	enthalpy per unit mass, J/kg
H	height, m
J	mass flux, kg/(m^{2}s)*Greek symbols*
L	length, m
$\dot{m}_e$	mass flow rate of evaporated water, kg/s
$\mathbf{N}$	unit normal vector
Re	Reynolds number
RH	relative humidity
S	enthalpy source term
Sc	Schmidt number
T	time, s
T	temperature, K
$\mathbf{V}$	velocity vector, m/s
W	width, m
Y	water vapour mass fraction

Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamics
y+	Dimensionless y distance to water-air interface
KTG	Kinetic Theory of Gases
NTC	Negative Temperature Coefficient
PID	Proportional–Integral–Derivative
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
SST	Shear-Stress Transport
VOF	Volume of fluid

Greek symbols

α	thermal diffusivity, m^2/s
δ	relative percentage error
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
τ	shear stress, Pa

Subscripts

a	air
e	evaporation
exp	experimental
i	species index
in	inlet
out	outlet
sim	simulated
t	turbulent
w	water; saturated air at water temperature

they are valid. Based on Sherwood number (ratio of the convective mass transfer to the rate of diffusive mass transport), Pauken [7] proposes some new correlations adjusted to his experimental data, with maximum errors of 8%.

Analogously, Asdrubali [8] uses a small climatic chamber to control environmental conditions, within which an aluminium container with water is located. Evaporation measurements are made by using a precision balance under the water container. Experiments are carried out under different water and air temperatures, air velocity and relative humidity. The author sets a prediction model of evaporation rate, adjusted through his experimental observations, which is compared with other correlations from literature, finding discrepancies up to 27%.

Jodat and Moghiman [9] make also a similar experiment in a wind tunnel in which the evaporation pan is sufficiently large to reduce convective edge effects. A wide range of flow conditions are analysed based on the values of Gr/Re^2, which approximates the ratio of the buoyancy and inertial forces, and from which evaporation rate seems to depend strongly. For the forced convection flow regimes, Gr/Re^2 is much less than one, while for the free convection, Gr/Re^2 is much greater than one. Gr/Re^2 is almost one for a combination of both natural and forced convection regimes. As pointed out by Pauken [7] for Gr/Re^2 > 5, the contribution of forced convection to the total evaporation rate was less than 10%. From Jodat and Moghiman [9], flows with Gr/Re^2 < 0.1 are considered forced convective flows; mixed convection for 0.1 < Gr/Re^2 < 5; and free convection for Gr/Re^2 > 5.

Finally, the work of Raimundo et al. [10] can be underlined, in which the study of evaporation rate is made from experimental measurements in a low speed wind tunnel and from numerical simulations (by using a 3D-CFD code). Authors conclude that there is a significant dependence of evaporation rate on air velocity.

Most of the former authors propose a correlation equation to predict evaporation rate, based on Dalton approximation [11] or on similarity theory. Although these correlations adjust well to the corresponding experiments, with maximum errors up to 10%, it is not possible to ensure their validity and extrapolation to other conditions and geometries. Thus, discrepancies greater than 80% can be found between correlations under the same conditions [12].

The strategy to predict evaporation rate by using numerical models can be very interesting due to its generality and because it may be applied in every situation and configuration. From a literature review and although very few studies can be found, the work by Raimundo et al. [10] is noteworthy. They extend an existing 3D-CFD code, based on the integration of the Reynolds-averaged Navier-Stokes equations, and they adapt turbulent model in order to get a direct calculation of evaporation rate. Turbulent k-ε model with wall functions to solve both velocity and water vapour concentration profiles at the boundaries. Wall functions were adapted to achieve better results at air-water interface. Assuming that turbulent mass diffusion is mainly led by advection and turbulent mechanisms, an expression dependent on the absolute value of local flow velocity was used for turbulent Schmidt number.

This work presents an exhaustive procedure of experimental validation of a new CFD-based methodology formerly described in Foncubierta et al. [13] to calculate water evaporation rate in indoor swimming pools. This methodology is based on some hypotheses that set boundary conditions at the air-water interface which are not dependent on experimental adjustments, allowing both the calculation of water evaporation rate and air flow distribution within the facility under different flow regimes and conditions. A common protocol for experimental measurements has been used, with a wide range of convective flow conditions with a special focus on those frequently found in this kind of environments: low velocities (0.08–0.54 m/s) and water and air temperatures in the ranges 24-28 °C and 26-30 °C, respectively [14].

Firstly, the experimental installation and procedure designed are described in detail. Secondly, the CFD methodology used to calculate evaporation rates is explained. Finally, a comparison and analysis of experimental and estimated results are shown.