Energy and Buildings 41 (2009) 311–319

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A scale model to evaluate water evaporation from indoor swimming pools

F. Asdrubali *

Department of Industrial Engineering, University of Perugia, Via G. Duranti 67, 06125 Perugia, Italy

ARTICLE INFO

Article history:
Received 11 February 2008
Received in revised form 28 August 2008
Accepted 5 October 2008

Keywords:
Evaporation
Heat loads
Swimming pools
Scale model

ABSTRACT

The evaluation of water evaporation from indoor swimming pools is a topic of considerable practical interest, since evaporation may cause the highest energy consumption of the pool plant. A purposely designed experimental apparatus was used to measure the water evaporation rate from a pool scale model inserted into a climatic chamber to control environmental conditions. The experimental data were obtained varying various parameters such as water temperature, air temperature, relative humidity and air velocity. The results were used to propose a prediction model for water evaporation which was compared to other methods found in the literature, showing a good agreement.

1. Introduction

The study of water evaporation from indoor swimming pools is a topic of major interest both for the design of HVAC—heating, ventilation and air-conditioning systems and of water heating plants: in indoor swimming pools, in fact, the highest thermal load is often due to water evaporation, which therefore represents the main source of energy consumption of the entire plant.

A precise evaluation of the evaporation flow rate in these basins is therefore very important, to the extent that it makes it possible to correctly design the air conditioning system and to reduce energy consumption. Furthermore, water evaporation adds moisture to the building atmosphere and the resulting high humidity may cause discomfort to the occupants and damage to materials by promoting rot and corrosion.

Water evaporation from free surfaces is a function of many parameters, such as water temperature, air temperature and relative humidity, air velocity, as well as number and kind of activity of the occupants. There are various studies in the literature concerning the evaluation of evaporation from indoor pools [1–4]; most of them have considered data from real, occupied or unoccupied pools, but there is no evidence of recent studies done on small-size scale models.

The main objective of this study is to develop data and relations of general validity to calculate the water evaporation flow from indoor swimming pools, starting from experimental investigations in various conditions of temperature, relative humidity and air velocity.

To this extent, an experimental apparatus was designed at the Thermotechnical Labs of the University of Perugia to carry out initial water evaporation measurements from a scale model of a swimming pool [5,6]; the apparatus, inserted into a climatic chamber, made it possible to control air temperature and relative humidity but not water temperature. The preliminary results encouraged the design and construction of an improved apparatus, which also allowed precise control of water temperature, as in real indoor swimming pools.

Measurement results were used to implement a correlation to predict evaporation and, therefore, to estimate heat loads in indoor swimming pools under different service conditions.

2. Literature review

Many methods for evaluating evaporation from water basins have been proposed over the years [7–9], although only a few are specifically related to indoor swimming pools. Some of them were derived from experimental measurements in real pools, others from energy balances of the pool or basin, others from the evaluation of the amount of condensate on the cooling coil of the air-conditioning unit, assuming that this is equal to the amount of water evaporated from the pool surface. Shah recently provided a summary of available methods [3,10,11] both for unoccupied and occupied pools: the two cases have to be discussed separately, since for various reasons evaporation is higher in occupied pools, most notably because of the increase in contact area between air and water. Occupants, in fact, cause waves, ripples and mist, increasing with the number of occupants and their activity.

* Tel.: +39 0 75 5853716; fax: +39 0 75 5853697.
E-mail address: fasdruba@unipg.it.

0378-7788/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2008.10.001

Nomenclature

A	surface of evaporation area (m^2)
D	diffusivity
E	evaporation rate (kg/(m^2 s); kg/(m^2 h), lbs/h)
G	mass flow rate (kg/s, g/h)
I	water latent heat of evaporation (kJ/kg)
K	mass transfer coefficient (referred to pressure) (kg/(Pa m^2 s))
L	water evaporation heat (kJ kg^{-1})
m	mass (kg)
N	number of pool occupants (–)
P	saturation pressure (Pa, Hg)
Re	Reynolds number (–)
Sc	Schmidt number (–)
Sh	Sherwood number (–)
t	time (s)
T	temperature (°C)
V	velocity (m/s)
Y	latent heat of evaporation (kJ kg^{-1})
W	specific humidity (kg of moisture/kg of dry air)

Subscripts

a	air
ev	evaporation
los	loss
max	pool area plus waves area
p	pool
r	room
un	unoccupied
v	ventilation
w	water

Greek letters

Δ	interval (–)
Δ	deviation (–)
υ	viscosity
ρ	air density (kg/m^3)
Φ	relative humidity (%)

Most of the empirical equations for unoccupied pools are of following type:

$$E = \gamma A_p (\Delta P)^n \quad (1)$$

where E is the water evaporation rate per unit area of the pool (kg/(m^2 s)); γ is a constant; A_p is the pool surface area (m^2); $\Delta P = P_w - P_r$ is the difference between water and room saturation pressures (Pa); and n is a value ranging from 1 to 1.2.

The most widely published and used correlation for water evaporation rates is the one proposed by Carrier in 1918 [12] and later reported in the ASHRAE Application Handbook [13]:

$$E = (0.089 + 0.40782\, V_a)\, A_p\, \Delta P/Y \quad (2)$$

where V_a is the velocity of air parallel to the water surface (m/s) and Y is the latent heat of evaporation of water (kJ/kg).

In Eq. (2), E, A_p and ΔP are measured respectively in kg/h, m^2 and Pa.

The expression is based on laboratory experiments in which air was blown above the water surface of a pool. Some authors suggest that the formula overestimates evaporation for unoccupied pools and recommend it for evaluating evaporation losses from occupied swimming pools [14].

Smith et al. [15,16] conducted tests on occupied and unoccupied swimming pools and gave empirical formulas based on these data; their equations are:

For unoccupied pools:

$$E = (C + 0.35 V_a) A_p\, \Delta P/Y \quad (3)$$

where C is a coefficient which depends on barometric pressure ($C = 72$ at 5000 ft elevation and $C = 69$ at sea level).

For occupied pools:

$$E = (0.068 + 0.063 F_u) A_p\, \Delta P/I \quad (4)$$

where F_u is the pool utilization factor ($F_u = A_{max}/A_p N$); A_{max} is the pool area A_p increased by waves area; I is the latent heat of evaporation of water (kJ/kg).

A different model has been proposed by Hannsen and Mathisen in [1]. Their formula for unoccupied pools may be written as

$$E = 3 \times 10^{-5} V^{1/3} (e^{0.06 T_w} - \Phi_a\, e^{0.06 T_a}) \quad (5)$$

where $V = [V_a^2 + (0.12(4(1-\Phi_a) - (T_a - T_w))^{0.5})^2]^{0.5}$; T_w is the water surface temperature (°C); T_a is air temperature (°C); and Φ_a is air relative humidity (–).

Shah [10] proposed a correlation based on the analogy between heat and mass transfer for unoccupied pools, later modified to improve accuracy:

$$E = K A_p \rho_w (\rho_r - \rho_w)^{1/3} (W_w - W_r) \quad (6)$$

where ρ is the air density (kg/m^3); ρ_r is the room air density, while ρ_w is the saturated air density; W is the specific humidity (kg of moisture/kg of dry air); and K is a constant.

In Eq. (5), $K = 40$ if $\rho_r - \rho_w < 0.02$; $K = 35$ if $\rho_r - \rho_w > 0.02$.

The correlation was evaluated against undisturbed water pool test data from various sources, covering a wide range of water temperatures (7.1–94.2 °C), air temperatures (6.1–34.6 °C) and air relative humidities (28–98%).

Shah recommends Eq. (6) for indoor water pools with undisturbed surfaces and unforced airflow over those surfaces.

He also proposed an empirical correlation based on test data from various sources for occupied pools:

$$E = A_p (0.113 - 0.0000175 A_p/N + 0.000059\, \Delta P) \quad (7)$$

Eq. (7) is recommended for normal activity occupied pools (N, number of pool occupants less than 45), under the following conditions: water temperature (25–30 °C), air temperature (26–31.7 °C) and air relative humidity (33–72%). Finally, Shah [11] also proposed another formula for pools with very intense activity such as diving and water polo.

As stated previously, some of the correlations mentioned are derived from energy balances and others from experimental measurements in real pools, but there is no evidence in the literature of measurements carried out on scale models, apart from some studies quoted by Shah in [11], some of which date back to more than 60 years ago and cover a range of air and water temperatures that is too wide to be considered reliable. The aim of this paper is therefore to provide new experimental results for evaporation rates from water basins, thanks to a scale model and an apparatus which allows one to accurately control all the main parameters influencing the phenomenon.