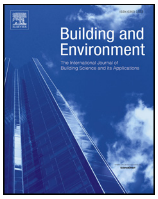
Building and Environment 145 (2018) 1–13

Contents lists available at ScienceDirect

Building and Environment

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



Experimental validation of the numerical model of air, heat and moisture flow in an indoor swimming pool

Piotr Ciuman*, Barbara Lipska

Department of Heating, Ventilation and Dust Removal Technology, Silesian University of Technology, Konarskiego 20, 44-100, Gliwice, Poland

ARTICLE INFO

Keywords:
Indoor swimming pool
Ventilation
Air flow variables
Measurement
CFD prediction
Experimental validation

ABSTRACT

Indoor swimming pools are facilities in which a ventilation system has a vital impact on the proper operation of the building, as well as the users' comfort, operating costs and the safety of the structure. The major problem in ensuring appropriate thermal-moisture conditions is the removal of moisture that is mainly gained from the surface of the water in the pool's basin. The aim of this paper was to experimentally identify the physical phenomena occurring in the actual indoor swimming pool and to evaluate whether the numerical model of the facility, developed with the use of Ansys CFX 14.5 software, correctly mapped these phenomena and how it should be improved in this field. Results of the experimental research of the air variables, carried out in various periods of the year, were used to identify the changes in the thermal-moisture conditions and to prepare boundary conditions for the numerical calculations, as well as to validate these simulations experimentally. The numerical model was improved with the use of the authors' own method of modelling moisture emission from the surface of the water. It was based on the implementation of literature formulas for calculating the value of this parameter in the software. The validation encompassed the indoor airflow pattern and the distribution of the air flow variables above the surface of the water and around the pool's basin. The improved numerical model was able to reproduce the actual conditions in the indoor swimming pool with good concurrence of the experimental and predicted values.

1. Introduction

Indoor swimming pools are facilities for recreational, sporting and therapeutic purposes. Their most important part is the pool's basin, which is the main source of heat and moisture. The sources of heat are also: lighting, radiators, people, evaporating water, heat penetrating the building's envelope and solar radiation. The sources of moisture, besides the surface of the water, are: the moist surface of the floor, people, and water attractions. Heat and moisture gains must be removed by the ventilation system to prevent deterioration of thermal-moisture conditions in a facility, especially the increase of specific air humidity.

In case of the lack of a ventilation system or if such a system was improperly designed, executed and operated, a series of negative phenomena may occur. They involve the thermal discomfort of swimmers and condensation of water vapour on cold surfaces, the temperature of which is lower than the indoor air dew point temperature. The latter can lead to i.e. fogging of windows, weakening of the building's structural elements, as well as the formation of fungi and mould.

The intensity of moisture evaporation depends on many factors, such as: the size of the surface of the water and the moist floor, the water temperature, the air temperature and relative humidity, the air velocity above the surface of the water, the number and activity of swimmers and the water circulation in the pool. The phenomenon of moisture evaporation from the surface of the water in the pool's basin is associated with the boundary layer between the indoor air and the surface of the water. The intensity of such evaporation is dependent on the difference in the partial pressure of the water vapour in the boundary layer and the indoor air.

In the literature, many correlations that have been validated experimentally can be found, on the basis of which the mass flux of evaporated moisture from the surface of the water can be calculated. However, there is no consensus among researchers as to the method of its calculation.

The most well-known correlation for the calculation of moisture emission from the surface of water is the Carrier formula [1]:

$$\dot{m}_w = \frac{F}{r}(0.0888 + 0.0783v)(p_w - p_i) \tag{1}$$

In this formula two constants are taken into account: 0.0888 W/

---

* Corresponding author.
E-mail addresses: piotr.ciuman@polsl.pl (P. Ciuman), barbara.m.lipska@polsl.pl (B. Lipska).

https://doi.org/10.1016/j.buildenv.2018.09.009
Received 2 April 2018; Received in revised form 5 September 2018; Accepted 6 September 2018

Nomenclature

$\dot{m}_w$	mass flux of emitted moisture (kg/s)
x_w	specific air humidity at the temperature of water surface (kg H_2O/kg dry air)
F	surface of water in pool's basin (m^2)
x_i	specific air humidity at room air dew point (kg H_2O/kg dry air)
v	air velocity above the water surface (m/s)
F_a	activity coefficient
r	latent heat of water at the temperature of water surface (kJ/kg)
B	evaporation coefficient (g/(m^2hhPa))
p_w	partial pressure of water vapour at the saturation state and the temperature of water surface (kPa)
ρ_w	air density at the temperature of water surface (kg/m^3)
p_i	partial pressure of water vapour at room air dew point (kPa)
ρ_i	air density at room air dew point (kg/m^3)
p	absolute pressure (kPa)
t_{ws}	temperature of water surface (°C)
φ_i	indoor air relative humidity (%)
t_w	temperature of water in pool's basin (°C)
m_w	mass of water vapour in the humid air (kg)
t_{dp}	air temperature at room air dew point (°C)
m_a	mass of dry air (kg)
t_i	indoor air temperature (°C)
y^+	wall distance

(m^2Pa) and 0.0783 (Ws)/(m^3Pa).

Smith et al. [2] recommended multiplying the results obtained with the Carrier formula by the value of 0.73.

ASHRAE [3] implemented the activity coefficient F_a into the Carrier correlation, the value of which is dependent on the degree of usage of the swimming pool.

The formula given in the VDI guidelines [4] involves the evaporation coefficient B, the value of which is dependent on the state of the surface of the water:

$$\dot{m}_w = FB(p_w - p_i)3600 \tag{2}$$

For the calm surface of the water, the evaporation coefficient B is equal to 5 g/(m^2hhPa).

In the Biasin & Krumme [5] correlation three experimental coefficients occur:

$$\dot{m}_w = F\left[-0.059 + \frac{0.0105(p_w - p_i)}{133.3}\right]3600 \tag{3}$$

Shah [6] made the moisture emission conditional upon the differential of the air density and the relative humidity values in the boundary layer and inside the facility, according to the correlation:

$$\dot{m}_w = FC\rho_w(\rho_i - \rho_w)^{1/3}(x_w - x_i)3600 \tag{4}$$

If the expression $(\rho_i - \rho_w) < 0$, the absolute value of the expression should be adopted. For $(\rho_i - \rho_w) > 0.02$ the coefficient is equal to $C = 35$, and for $(\rho_i - \rho_w) < 0.02$ this value is equal to $C = 40$.

In the case of any research, in which it is necessary to take into account the phenomenon of moisture emission from the surface of the water in an indoor swimming pool, a problem with the selection of the most accurate formula occurs.

In the literature, examples of research on indoor swimming pools' ventilation systems can be found. For a large swimming pool in Canada [7] both experimental and numerical research was carried out. The results of numerical simulations were validated to reproduce the air velocity, temperature and humidity distributions. Also, the influence of external climatic conditions and the swimmers on the internal conditions of the facility was evaluated. The comparison of numerical results with experimental measurements showed good agreement regardless of the turbulence model. For the same indoor-swimming pool in Canada [8] the numerical evaluation of the thermal comfort of occupants, indoor air quality and heat losses was carried out. The indoor air quality and the thermal comfort of occupants were evaluated using respectively the concept "age of air" and the comfort index EDT (*Effective Draft Temperature*). The experimental validation proved the good agreement of the numerical results with the results of the measurements. The calculated age of air showed a relatively poor ventilated zone due to the weak diffusion of the inlet air, while the calculated EDT indicated that the discomfort caused by the sensation of heat predominates in the swimming pool whether in summer or in winter. The proposed modification showed improvement in this field. In the facility in Egypt [9] the impact of the air supply parameters on the mass flux of evaporated water from the pool and the air quality inside the building were examined. With the use of CFD numerical simulations and experimental data, distributions of air velocity, temperature and relative humidity were validated. In the indoor swimming pool in Denmark [10] the relationship between water evaporation from the pool's basin and air flow in the facility was examined with the use of numerical simulations. Shah's evaporation model was used to determine the value of the mass flux of emitted moisture and carry out an analysis of the numerical distributions of the air velocity, temperature and relative humidity. In the school's indoor swimming pool in Poland [11] thermal comfort conditions were analysed and evaluated with the use of CFD numerical predictions and the following indexes: PMV (*Predicted Mean Vote*), PPD (*Predicted Percentage Dissatisfied*), DR (*Draught Rate*), ADPI (*Air Diffusion Performance Index*). In the facility in Canada [12] research on airflow and indoor air quality was carried out with the use of numerical simulations conducted in TRNSYS software. The results of these simulations were compared with the results of the experimental research of the air flow variables. Then they were applied to the analysis of the air flow characteristics and the evaluation of the air quality with the use of PMV and PPD indexes and the heat index HD (*Humidex*). For a sporting facility designed in Italy [13] the indoor air velocity, temperature and relative humidity distributions were analysed, with the use of numerical simulations, to evaluate the operation of the ventilation system and the possibilities of providing thermal comfort.

Moreover, the results of experimental research on evaporation rate with the use of scale models are available. Gómez et al. [14] presented an experimental procedure at the laboratory scale model in wind tunnel. It was developed to validate a new CFD-based method to estimate water evaporation in indoor swimming pools. The validation of numerical results proved that the modelling strategy proposed is a promising tool, while the average relative errors equalled to 9% for the typical mixed convection flows in the indoor swimming pools. In the paper [15] the results of evaporation rate measurements are presented for scale models and full-scale indoor swimming pools. Air temperature, air humidity, water temperature at the surface and air velocity above the surface, along with the heat balance of the basin water were measured, as well. Blázquez et al [16] presented a new methodology with the use of a numerical model to estimate water evaporation rate in indoor swimming pools. The model was experimentally validated with the data obtained from three test chambers and a real swimming-pool. The results were quite satisfactory with low relative errors. Asdrubali [17] presented experimental investigation of water evaporation from a scale model of a swimming pool. Measurement results were used to implement a correlation to predict evaporation rate and to estimate heat loads in indoor swimming pools. A proposed model for water evaporation was compared to other literature models and a good agreement was found. In the paper [18] the investigation of the