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Simulation of airflow with heat and mass transfer in an indoor swimming pool by OpenFOAM

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ABSTRACT

Several CFD (computational fluid dynamics) simulations of the three-dimensional airflow with heat and mass transfer in a complex geometry indoor swimming pool were performed using the OpenFOAM software. A solver has been developed to take into account the mass transfer and the appropriate thermal boundary conditions. Several turbulence models RANS (Reynolds-Averaged Navier-Stokes) types were used. The comparison of numerical results with experimental measurements of air velocity, temperature and humidity showed good agreement regardless of the turbulence model. In order to evaluate the weather effect on the indoor atmosphere of the swimming pool, two simulations were carried out with winter and summer weather conditions. Their comparison showed a very small effect on the internal environment which is manifested by a greater temperature stratification in winter. Furthermore, the effect of swimmers on the indoor atmosphere of the swimming pool was evaluated and found to be of great importance. The main advantageous effect is the homogenization of the temperature and the specific humidity in the occupied space. On the other hand, its major adverse effect is the increase of the specific humidity in the air.

1. Introduction

During the last years, the indoor air quality and thermal conditions in large enclosed sports spaces have become a major preoccupation both for their impact on the health and productivity of the occupants as well as for their energy and environmental impacts. Several CFD (computational fluid dynamics) studies using different codes have been carried out to evaluate the performances of enclosed sports spaces such as hockey arenas [1–4] and sports halls [5,6]. Galanis and his team [1–3] modeled the airflow in a ventilated arena taking into account heat and mass transfer. Bellache et al. [1] modeled the two-dimensional steady state using Phoenics software. Omri and Galanis [2] used Ansys-Fluent to study the steady turbulent mixed convection while Omri et al. [3] focused on the transient case. Their results show that the disposition of air inlets and outlets influences heat losses and that the humidity has little influence on the temperature field. Furthermore, using radiant heating panels affects all the inner envelope temperature, especially that of the ice. However, in several studies [7–10] the radiation exchange between the walls of enclosed spaces is neglected since the temperature difference are small. Rajagopalan and Luther [5] used IES virtual environment-microflow CFD software to study the thermal and ventilation performance of a naturally ventilated (assisted by ceiling fans) sports hall within an aquatic center. Lam and Chan [6] used a CFD program EXACT3 to investigate the temperature distribution and air movement within an air-conditioned gymnasium.

Despite the studies mentioned above, only few CFD studies have considered the similar conditions of indoor swimming pools, which are characterized by high energy needs for heating and air conditioning as well as by stringent requirements for comfort. Koper et al. [8] is in general and probably the best-known paper concerning the swimming pool, they used the Ansys-Fluent software and the turbulence model with six Reynolds equations to analyze the conditions in an indoor swimming pool with several basins. The basins were modeled as an isothermal plane source of humidity with a constant emission of humidity over their entire surface. They determined the heat flux penetrating each wall. In a similar study using Ansys-Fluent software and the standard k-ε model, Li and Heiselberg [9] considered stationary turbulent flow. The entire space was discretized by a structured grid. Heat fluxes at the walls were based on measured values. However, they neglected sunshine effects despite a fully glazed facade. The CFD simulation results seem in good agreement with the measured values. Ciuman et al. [10], in their CFD simulation with Ansys-CFX software,

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Nomenclature

Cp	specific heat capacity, J kg^{-1} K^{-1}
d	hydraulic diameter, m
g	gravitational acceleration, 9.81 m s^{-2}
H	characteristic length, m
k	turbulent kinetic energy, m^2 s^{-2}
$\dot{m}$	mass flow rate, kg s^{-1}
N_x	number of grid lines in the x direction, (dimensionless)
N_y	number of grid lines in the y direction, (dimensionless)
N_z	number of grid lines in the z direction, (dimensionless)
p	pressure, kg m^{-1} s^{-2}
Pr	Prandtl number, (dimensionless)
Sc	Schmidt number, (dimensionless)
T	temperature, °C
ΔT_0	temperature difference between the inlet and the outlet, °C
U	velocity, m s^{-1}
w	specific humidity, kg$_{water}$ kg$_{air}^{-1}$
$Y+$	dimensionless distance, dimensionless

Greek letters

β_T	thermal expansion coefficient, K^{-1}
β_M	mass expansion coefficient, dimensionless
ε	dissipation rate of turbulent energy, m^2 s^{-3}
Φ	relative humidity, dimensionless
ρ	mass density, kg m^{-3}
ω	frequency, s^{-1}
υ	kinematic viscosity, m^2 s^{-1}

Subscripts/Superscripts

0	inlet
l	laminar
r	reference
t	turbulent
out	outside
s	surface
w	wind

showed the importance of the resolution effect of the unstructured mesh on the flow structure. Their results indicate a significant difference with experimental temperature measurements, which could be justified by the inaccuracy of reproducing the heat losses through the building envelope. Abo Elazm and Shahata [11] for their part, they evaluated the evaporation rate of the water to determine the air exchange rate required to ensure good air quality. In their simulation with the Ansys-Fluent software, they used a specific humidity transfer equation which is not coupled with the other conservation equations. The results obtained showed that the supply air velocity and temperature have great effect on the rate of evaporation.

Such CFD studies of the conditions in indoor swimming pools must take into account heat and mass transfer between the water and air as well as between the air and inside surfaces of the envelope where condensation can cause mildew. To study these complex phenomena, several hypotheses have been considered. The humid air is treated as a mixture of two ideal gases (dry air and vapor), whose density is determined by the ideal gas law and pressure is the sum of the partial pressure of its components [12]. It is also assumed that at the vapor-liquid interface, the two phases are in thermodynamic equilibrium and the phase change occurs under saturation conditions. So, the interface is considered saturated at the liquid water temperature. Several authors [11–14] have adopted this hypothesis. To take into account buoyancy effects, the Boussinesq approximation is often adopted for simulations of airflow with heat transfer in enclosed spaces for its simplicity. This approximation is based on the assumption that the density is constant except in the buoyancy term [15]. Its validity has been the subject of several studies [1,2,16–18] which showed that it provides accurate results for small differences in temperature and concentration. It should be noted that it has also been used to study flow with heat and/or mass transfer in large enclosed spaces [12,19–21].

The phenomena specific to two phases environments (water-air) are generally neglected, because the mass flow caused by the temperature gradient (Soret effect) and the heat flux caused by the mass gradient (Dufour effects) are small [12,22]. An adequate numerical simulation of the different turbulent transfers taking place in an indoor swimming pool requires computer codes that are able to model effectively the chaotic character of these phenomena and provide accurate numerical solutions at a reasonable cost. In the present study, the simulations were performed using OpenFOAM (Open Field Operation and Manipulation) open source software that is based on the finite volume method [23]. The great asset of OpenFOAM is its ability to implement new solvers, turbulence models and boundary conditions. This therefore makes it also suitable for scientific research and industrial applications. Its major inconveniences are the absence of certification, the quality of graphical as well as the incomplete and dispersed documentation [23].

Although previous studies have been cited, no work has considered taking into account the effect of climatic conditions and the effect of swimmers on the internal environment of swimming pool. Therefore, this paper has two major objectives:

- Validate the solver and boundary conditions developed on OpenFOAM to reproduce the air velocity, temperature and humidity distributions in a large indoor swimming pool.
- Evaluate the influence of external climatic conditions and the swimmers on the internal atmosphere of the pool (flow structure, fields of temperature and humidity, energy consumption).

2. Pool description

The present study concerns a semi-Olympic pool located at Bishop's University in Sherbrooke (Quebec, Canada). The space considered consists of a large enclosure with complex geometry, of roughly trapezoidal shape (Fig. 1) and dimensions of (25 m × 34.5 m × 8 m) with the following characteristics:

- Very humid environment (compared to other large enclosed spaces such as hockey arenas and gymnasia) with water evaporation and condensation phenomena influencing heat transfer and occupants comfort.
- The control of the air temperature in the pool is ensured exclusively by the HVAC (heating, ventilation and air conditioning) system (no auxiliary heating system).
- Lighting is provided by 32 identical units using fluorescent tubes with a lighting power density (LPD) of 2 W/m^2 for each unit (according to the manufacturer).