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The Impact of Modeling Method of Moisture Emission from the Swimming Pool on the Accuracy of Numerical Calculations of Air Parameters in Ventilated Natatorium

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Abstract**—**The aim of presented research was to improve numerical predictions of air parameters distribution in the actual natatorium by the selection of calculation formula of mass flux of moisture emitted from the pool. Selected correlation should ensure the best compliance of numerical results with the measurements' results of these parameters in the facility. The numerical model of the natatorium was developed, for which boundary conditions were prepared on the basis of measurements' results carried out in the actual facility. Numerical calculations were carried out with the use of ANSYS CFX software, with six formulas being implemented, which in various ways made the moisture emission dependent on water surface temperature and air parameters in the natatorium. The results of calculations with the use of these formulas were compared for air parameters' distributions: Specific humidity, velocity and temperature in the facility. For the selection of the best formula, numerical results of these parameters in occupied zone were validated by comparison with the measurements' results carried out at selected points of this zone.

Keywords**—**Experimental validation, indoor swimming pool, moisture emission, natatorium, numerical calculations, CFD, thermal and humidity conditions, ventilation.

I. Introduction

THERMAL-Moisture conditions in natatoria are affected by heat and moisture gains from various outdoor and indoor sources. They involve heat gains or losses through building envelope and internal partitions. Heat can also flow from central heating radiators and lighting. Water in pool exchanges heat with surrounding air by convection. The source of heat and moisture are also people. However, the main source of moisture is pool’s water surface and surface of moist floors.

Natatoria are usually ventilated and the goal of ventilation system is to take and remove excess heat and moisture gains from such facility. Modern ventilation design can be supported in this respect by numerical modeling of air, heat and moisture flow with the use of CFD method. Numerical calculations allow predicting thermal comfort conditions in natatoria at the design stage of ventilation.

The issue of numerical modeling CFD of air and moisture flow in natatoria was analyzed by [1]-[3], who numerically and experimentally studied the impact of supply jets on moisture emission from the swimming pool. Experimental validation of numerical calculations, carried out by [4], indicated the need to improve modeling method of moisture emission from the water surface. This emission depends on water temperature, but also to a large extent on air parameters in a room, which during the course of numerical calculations change. On the other hand, the value of mass flux of emitted moisture has an important effect on numerically predicted air parameters distribution in a natatorium, especially on its humidity. Therefore, it is advisable to implement this emission in a form of water and air parameters correlation, as in case of calculations carried out for ice rinks [5]. In literature, a wide range of formulas describing mass flux value of emitted moisture can be found. They were listed in [1].

The purpose of presented research was to enhance numerical modeling of air parameters distribution in the actual natatorium by the selection of formula for calculating the mass flux of emitted moisture from the swimming pool. The correlation should ensure the best compliance of numerical and experimental results of air parameters in the facility.

II. Description of the Natatorium and Its Numerical Model

The facility used for tests was the actual school natatorium in Gliwice (Poland) (Fig. 1), with dimensions: Length 17.55 m, width 11.6 m and the average height 4.35 m. The dimensions of the pool were: Length 12.5 m, width 7 m.

Internal partitions of the tested natatorium were: The north-east wall, the south-east wall and the floor of the natatorium. The rest of the partitions were external. In the south-west wall were windows. Around the pool was a flooring called the beach.

The natatorium was ventilated by the supply-exhaust ventilation. The air was supplied into the natatorium by 7 inlet grilles mounted in the supply duct in the suspended ceiling along the north part of the beach and by 12 inlet slots located at the bottom along the windows. The air was exhausted by 12 outlet grilles mounted in the exhaust duct in the ceiling recess (6 outlet grilles on opposite sides of the recess).

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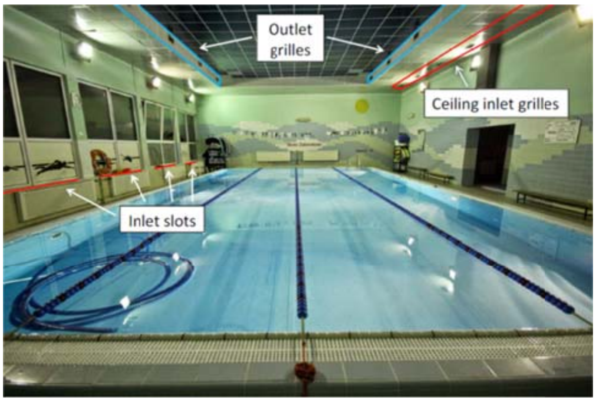

Fig. 1 View of the interior of school's natatorium [6]

The numerical model of tested natatorium, presented in Fig. 2, was prepared with the use of CFD software – ANSYS CFX. Actual dimensions of the natatorium, its geometry and water surface were taken into consideration and the distribution system of ventilation air was modeled. On internal and external partitions, penetrating heat fluxes were set. Water surface was modeled as a surface of constant temperature t_w = 29.75 °C.

The inlet grilles were modeled as rectangles with dimensions: 0.31 m x 0.11 m, inlet slots as rectangles of width 0.002 m and average length 0.87 m; similarly, the outlet grilles, with dimensions 0.31 m x 0.11 m. Radiators and lamps were modeled as well.

Numerical calculations were carried out with the use of ANSYS CFX software in steady, non-isothermal conditions. In simulations, the SST turbulence model from EVM models group was used, as well as standard Prandtl wall functions. Unstructured discretization grid was built with 10105448 tetrahedral elements and 2015095 nods. Additionally, the mesh refinement was introduced 20 cm above the water surface. The discretization grid used for the research is presented in Fig. 3.

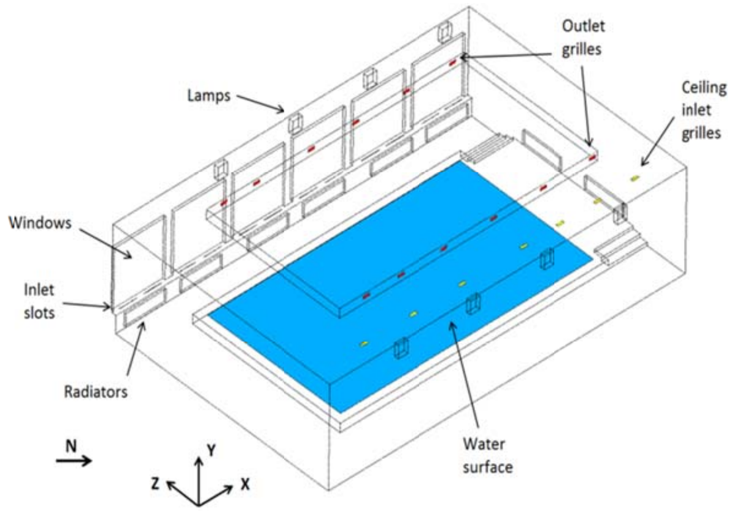

Fig. 2 Numerical model of the half of the natatorium

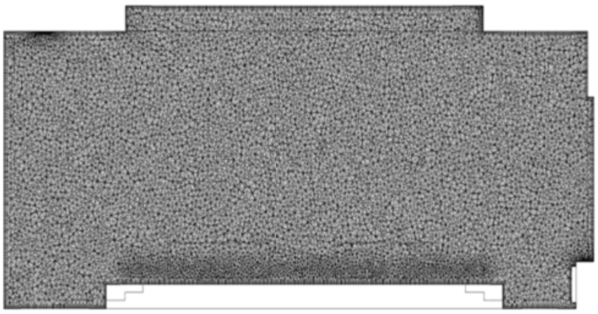

Fig. 3 Discretization grid used for the research

III. Preparation of the Boundary Conditions

The boundary conditions for numerical calculations were prepared on the basis of facility's stocktaking and results of air parameters' measurements carried out in the natatorium. These measurements included: Measurement of speed and temperature of supply air in inlets with the use of Testo-435 thermo-anemometer, measurement of relative humidity of supply air in inlets with the use of AR235 APAR temperature and relative humidity register and measurement of pool water temperature with the use of DRT-10 Sensor thermometer. Temperature and relative humidity of the outside air was read on the basis of the data provided by the local meteorological station, located at a distance of 635 m from the natatorium. These parameters could be used as a basis to determine the value of specific humidity, due to the fact that in the air ventilation unit neither dehumidifying nor humidifying of ventilation air occurred. Heat transfer coefficients of building partitions were adopted on the basis of facility's stocktaking.

Based on the measurements, the boundary conditions were calculated: mass flow of air supplied through ceiling inlet grilles and inlet slots, water surface temperature, mass flow of evaporating moisture from moist floors. Convective and radiation heat flows from radiators and lamps were determined on the basis of known values of their power.

The boundary conditions for the natatorium are presented in Table I.

TABLE I
THE BOUNDARY CONDITIONS FOR THE NATATORIUM

Mass flow of supply air	Ceiling inlet grilles	
	0.025 kg/s	
	Inlet slots	
	0.020 kg/s	
Supply air temperature	36ºC	
Outside air temperature	9ºC	
Specific humidity of supply air	0.00409 kg H_2O/kg of dry air	
Water temperature	31ºC	
Water surface temperature	29.75ºC	
Mass flow of evaporating moisture from the moist floors	0.00105 kg/s	
Heat flow from a single lamp	Radiation	Convection
	395.2 W/m^2	592.8 W/m^2
Heat flow from a single radiator	Radiation	Convection
	462.8 W/m^2	694.2 W/m^2

The values of these conditions were constant in all analyzed variants. Only one condition was variable – moisture emission from the pool. This condition was presented in a form of function, which was implemented into ANSYS CFX and allowed to determine the emission in each point of the discretization grid at the water surface. It depended on air parameters' values above the pool during the course of numerical calculations. In presented research for calculations of mass flux of emitted moisture E, kg/s from the swimming pool's water surface A, m^2 six correlations were used.

CARRIER formula [7] was recognized as a primary correlation:

$$E = \frac{A}{h_w} \cdot (0.0888 + 0.0783 \cdot V) \cdot (p_w - p_i) \tag{1}$$

where V is air velocity over water surface, m/s; p_w is saturation vapor pressure taken at surface water temperature, kPa; p_i is saturation pressure at room air dew point, kPa; h_w is latent heat required to change water to vapor at surface water temperature, kJ/kg.

Smith et al. [8] recommended that results of the Carrier formula should be multiplied by 0.73.

Ashrae [9] introduces to Carrier formula multiplying activity factor F_a, which is equal to 0.5 for unoccupied pool.

German standard VDI 2089 [10] recommends the correlation, in which evaporation factor is introduced, B = 5 for calm pool surface:

$$E = A \cdot B \cdot (p_w - p_i) \cdot 3600 \tag{2}$$

In Biasin & Krumme formula [11], for unoccupied pool, three experimental factors occur:

$$E = A \cdot [-0.059 + [0.0105 \cdot (p_w - p_i)] \cdot 133.3] \cdot 3600 \tag{3}$$

Shah [12] expressed moisture emission depending on the difference of air density and air specific humidity above the water surface and in the room:

$$E = A \cdot C \cdot \rho_w \cdot (\rho_i - \rho_w)^{1/3} \cdot (x_w - x_a) \cdot 3600 \tag{4}$$

where C = 35, for (ρ_i - ρ_w) > 0.02; C = 40, for (ρ_i - ρ_w) < 0.02; x_w is air specific humidity taken at surface water temperature, kg H_2O/kg d.a.; x_i is air specific humidity at room air dew point, kg H_2O/kg d.a.; ρ_w is air density taken at surface water temperature, kg/m^3; ρ_i is air density at room air dew point, kg/m^3.

For the same water and air parameters, the biggest value of moisture mass flux is obtained with the use of Carrier formula, and the lowest, equal to about 30% of the biggest value, on the basis of Biasin & Krumme formula. Smith et al. formula provides the value equal to 73% of the biggest one, Shah 67%, Ashrae 50%, and VDI 35%.

IV. Results of Numerical Calculations

Numerical calculations of air parameters distribution in the natatorium were carried out for 6 presented formulas for moisture emission calculations.

Results of numerical calculations were presented in the form of parameters' maps in two planes: X = 13.9 m (passing through the ceiling inlet grill and the inlet slot) and Y = 0.6 m (0.2 m above the water surface, on the level of swimmers' heads). Distributions of speed, temperature and specific humidity were analyzed. In case of each map, red color means values exceeding scale range.

In Fig. 4, distribution of air specific humidity in the natatorium is shown. In case of Carrier formula, predicted values were the biggest and almost in whole natatorium their distribution was aligned. The exception was the region close to the inlet grilles, because of lower specific humidity values of supply jets. The range of the highest air specific humidity values was smaller for Smith et al. formula, and even smaller for Shah formula. In case of Ashrae formula, that region occurred only above the water surface and in the rest of natatorium values were significantly lower than in case of previous formulas. For VDI formula, the biggest values of air specific humidity occurred only locally above the water surface. With the use of Biasin & Krumme formula, definitely the lowest values of air specific humidity were predicted. In case of Carrier, Smith et al. and Shah formulas, on vertical plane, the biggest values of this parameter occurred almost along whole height of the facility. In case of Ashrae, VDI and Biasin & Krumme the region of biggest values occurred only close to the water surface.

In Fig. 5, distribution of air speed in the natatorium is shown. The length and width of jets supplied by inlet grilles were similar in each case. For jets supplied by inlet slots, such comparison was more difficult because of jet's deflection off vertical axis, different for each case. The longest jets were predicted for Carrier, Smith et al. and Shah formulas. The range of air speed values and mixing degree of air in case of each correlation was similar, both on vertical and horizontal plane. The differences were caused by greater movement of moisture from the water surface toward the top of the room, when the emission of moisture is bigger.

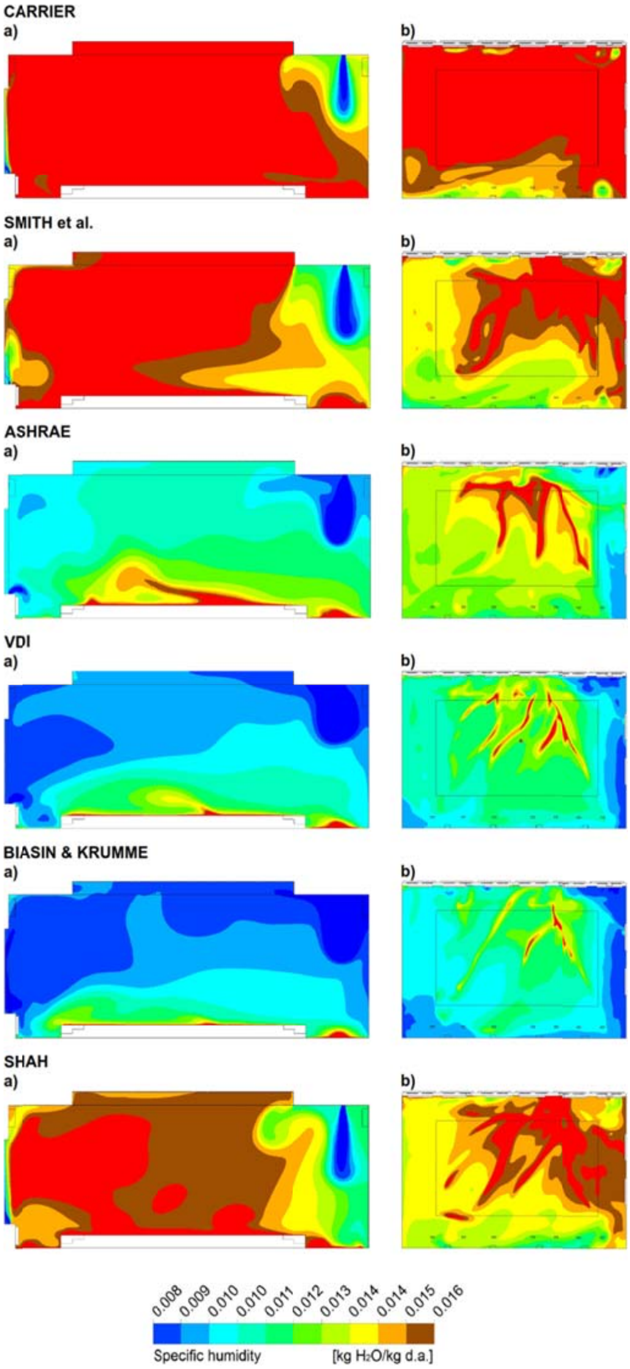

Fig. 4 Air specific humidity distribution in the natatorium on plane: (a) X = 13.9 m, (b) Y = 0.6 m (0.2 m above water surface)

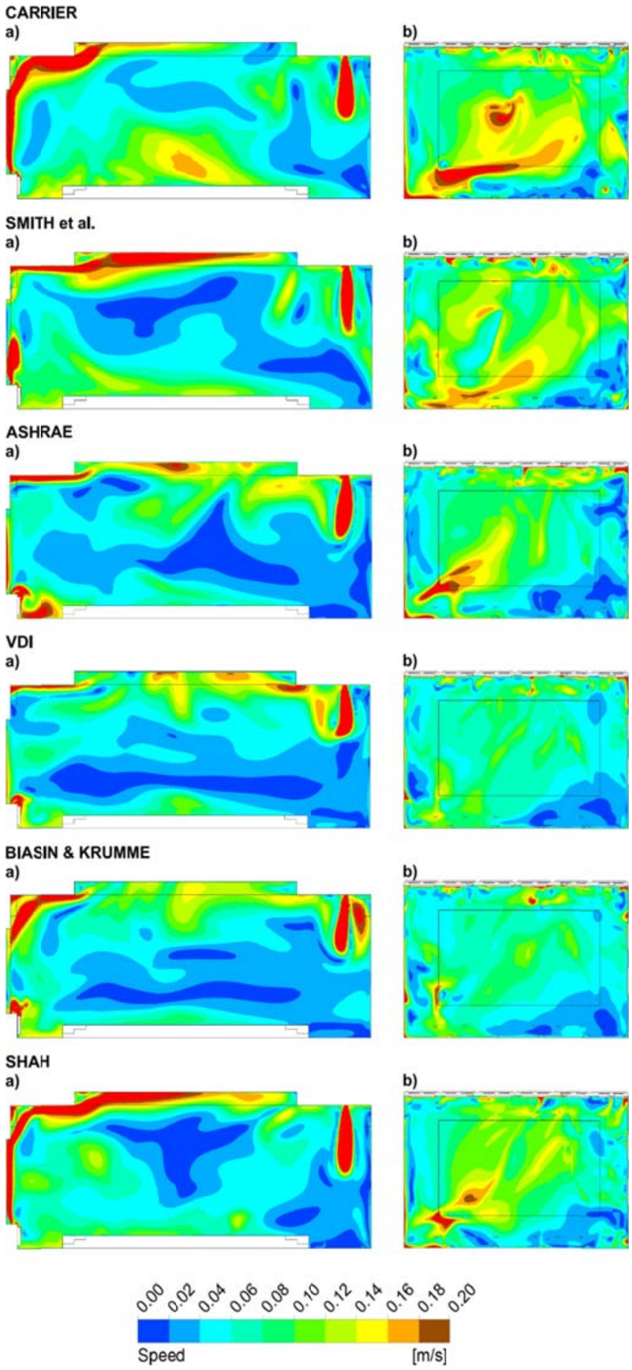

Fig. 5 Air speed distribution in the natatorium on plane: (a) X = 13.9 m, (b) Y = 0.6 m (0.2 m above water surface)

No significant impact of different formulas for moisture emission calculations on air temperature distribution in the natatorium was observed, as shown in Fig. 6. Across the facility, air temperature was aligned, at 31 °C. On horizontal planes, in some parts of the natatorium lower values of air temperature were predicted by about 1°C. Minor differences can be observed in case of Biasin & Krumme, Ashrae and VDI formulas, for which higher values of air temperature were obtained below the ceiling, and the region of lower temperature on horizontal plane encompassed bigger part of the natatorium.

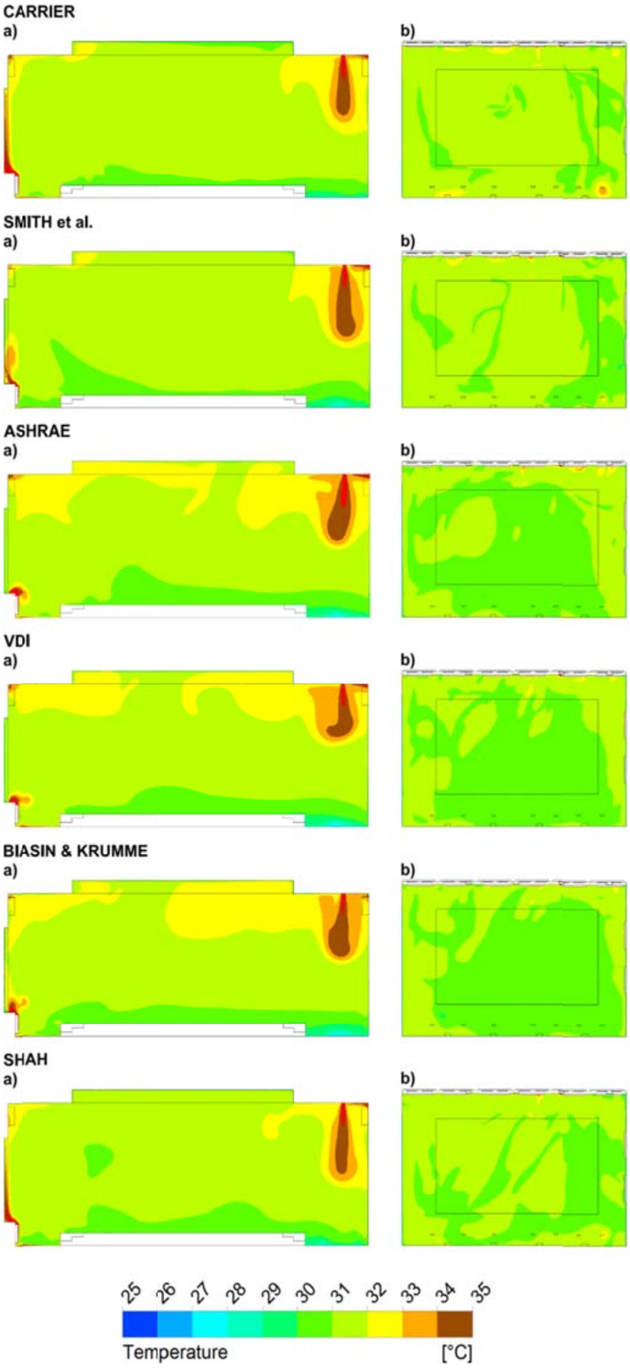

Fig. 6 Air temperature distribution in the swimming pool on plane: (a) X = 13.9 m, (b) Y = 0.6 m (0.2 m above water surface)

V. Validation of Numerical Calculations

Validation was performed for the predicted values of averaged air specific humidity, speed and temperature obtained with the use of each formula by comparison with the measurements' values obtained in the real facility. The measurements were carried out with the use of SENSOANEMO 5100SF Sensor thermos-anemometers with omnidirectional, spherical speed sensors and AR235 APAR temperature and relative humidity registers. The measurements took place in 6 measuring axes P1 - P6, deployed evenly in the middle of the beach's width on four levels – 0.1 m; 0.6 m; 1.1m; 1.7 m and in two points above the water surface (W1 and W2) at the height of 0.6 m (0.2 m above the water surface). Deployment of measuring points is presented in Fig. 7.

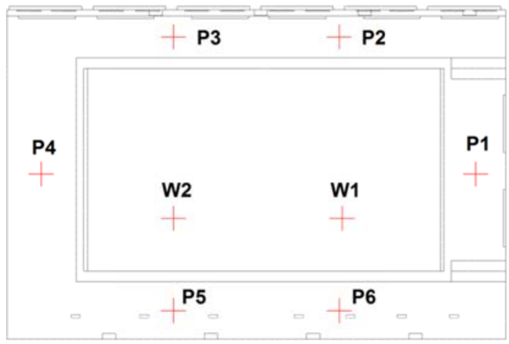

Fig. 7 Deployment of measuring points in the natatorium

In Fig. 8, validation results of air specific humidity and speed are presented for the measuring axis P2, located on the side of the windows, and for the measuring point W1, located on the side of the inner wall.

In case of air specific humidity values (Fig. 8 (a)), the closest results to measurements' values were obtained for VDI formula. Predicted values were within the range of measuring error on each level, except for 0.1 m, where they differed only slightly from error's range. Good compliance of results was also obtained for Carrier and Biasin formulas, which were within the range of measuring error at 1.1 m and 0.6 m, and on the other levels differed slightly. The worst compliance of results was obtained for Smith et al. formula. In point W1, the most accurate results were predicted for ASHRAE formula, which were almost identical with the measurement. Values close to the range of measuring error in this point were obtained for VDI and Shah formulas.

The closest speed values to the measurement values were obtained with the use of VDI and Smith et al. formula (Fig. 8 (b)). For each formula, the values were similar to each other and within the range of measuring error or in its vicinity. In case of W1 point the values obtained for VDI, Smith et al. and Biasin & Krumme formulas were identical and the closest to the measurement value and were on the verge of measuring error.

Due to the small impact of moisture emission on air temperature in the natatorium, also validation results for this parameter are identical for each formula. Therefore, it is not presented.

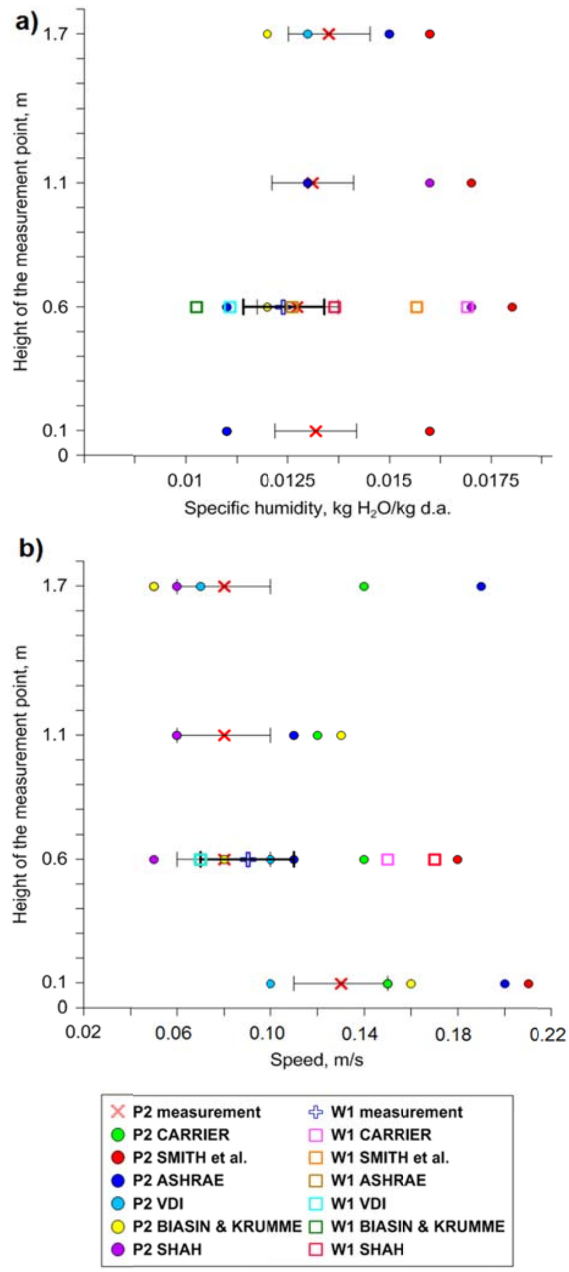

Fig. 8 Validation of (a) air specific humidity value and (b) air speed value for the measurement axis P2 and W1 point

VI. Conclusion

1. Mass flux of emitted moisture from swimming pool on one hand depends on air parameters' values in the natatorium, but on the other hand, its value has an impact on the distribution of these parameters. Therefore, for the improvement of numerical modeling it is advisable that the boundary condition in a form of moisture flux was not set as a constant value in calculations, but was implemented into software in a form of function. In literature various forms of these formulas appear. Numerical predictions of air parameters distribution in natatoria should be preceded by a selection of the best formula in given conditions.
2. The formulas used for moisture emission calculations from the swimming pool had an impact mainly on predicted distribution of air specific humidity in the natatorium. Their influence over air speed values was smaller, and in case of air temperature, it was not observed at all.
3. The best compliance of numerical predictions of air specific humidity and speed with the measurements' results, in selected axis and point, was obtained with the use of VDI formula. Therefore, this formula will be used in further numerical research of airflow in the natatorium.

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