Experimental-numerical method of selecting the model of moisture emission from the surface of water in a swimming pool basin

Eksperymentalno-numeryczna metoda wyboru modelu emisji wilgoci z lustra wody basenowej

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The issue of indoor swimming pool ventilation is very complex, which is a serious problem in their proper design and modernization. The difficulty is that in Poland there are no uniform regulations and standards regarding the required values of ventilation air parameters, the method of calculating moisture emission and the value of the ventilation air volume flow rate. In research, design and modernization of ventilation systems for swimming pools, various methods are used to determine the emission of moisture from the water in the swimming pool basin and there is no complete information as to which of them best reflects the actual thermal-moisture and airflow phenomena. This paper presents a developed and validated research method related to the modeling of moisture emission from the pool water surface, which can be used for the modernization of ventilation systems in the existing indoor swimming pools, due to the need to improve thermal-moisture conditions.

Keywords: indoor swimming pool, moisture emission, experimental research, numerical modeling CFD

Problematyka wentylacji hal pływalni jest bardzo złożona, co stanowi poważny problem we właściwym ich projektowaniu i modernizacji. Utrudnieniem jest również to, że w Polsce brak jest jednolitych przepisów i norm odnośnie do wymaganych wartości parametrów powietrza wentylacyjnego, sposobu obliczania emisji wilgoci oraz wartości strumienia objętości powietrza wentylacyjnego. W badaniach, projektowaniu i modernizacji systemów wentylacji hal pływalni stosowane są różne metody wyznaczania emisji wilgoci z wody w niecce basenowej i nie ma pełnych informacji, która z nich najlepiej odwzorowuje rzeczywiste zjawiska cieplno-wilgotnościowe oraz przepływu powietrza. W niniejszym artykule zaprezentowano opracowaną i sprawdzoną metodę badawczą związaną z modelowaniem emisji wilgoci z lustra wody basenowej, która może być zastosowana przy modernizacji układów wentylacji w istniejących obiektach krytych pływalni, z uwagi na konieczność poprawy warunków cieplno-wilgotnościowych.

Słowa kluczowe: hala pływalni, emisja wilgoci, badania eksperymentalne, modelowanie numeryczne

Nomenclature

$\dot{V}_N$	Supply air volume flow rate (m^3/h)
$\dot{W}$	total mass flux of emitted moisture (kg/h)
$\dot{m}_w$	mass flux of emitted moisture from the pool water surface (kg/s)
$\dot{m}_p$	mass flux of emitted moisture from the wet floors (kg/s)
F	surface of pool water (m^2)
F_p	surface of wet floors (m^2)
v	air speed above the water surface (m/s)
r	latent heat of water at the temperature of water surface (kJ/kg)
p_w	partial pressure of water vapour at the saturation state and the temperature of water surface (kPa)
p_i	partial pressure of water vapour at room air dew point (kPa)
x_w	specific air humidity at the temperature of water surface (kg H_2O/kg d.a.)
x_i	specific air humidity at room air dew point (kg H_2O/kg d.a.)
x_N	specific humidity of the supply air (kg H_2O/kg d.a.)
t_i	indoor air temperature (°C)
t_m	wet bulb temperature (°C)
ρ_w	air density at the temperature of water surface (kg/m^3)
ρ_i	air density at room air dew point (kg/m^3)
ρ_N	supply air density, kg/m^3
F_a	activity coefficient
B	evaporation coefficient ($g/(m^2hhPa)$)

Introduction

Indoor swimming pools are facilities that must be designed, built and then used in accordance with technical and construction regulations to provide their occupants with safe and appropriate operating conditions, as well as to ensure that energy consumption is kept at a reasonably low level. The proper functioning of the facility, thermal comfort of occupants and safety of the construction are significantly influenced by thermal, moisture and airflow conditions. Shaping the proper microclimate in these facilities depends on many factors, mainly on a properly designed, constructed and operated ventilation system, which in winter often also serves as air heating.

The most important part of an indoor swimming pool is a pool basin. Its size and the temperature of water it contains depend on its purpose. It is the main source of heat and moisture. The intensity of moisture evaporation depends on many factors, such as: surface of pool water and wet floors, water temperature, air temperature and relative humidity, air speed above the water surface, the number and activity of

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swimmers, as well as the type and number of water attractions.

The complexity of issues affecting the functioning of the swimming pool and lack of uniform Polish standards and regulations regarding the recommended air parameters in such facilities, makes it necessary for designers to refer to foreign standards or data contained in literature sources. Therefore, it is difficult to design a ventilation system that will function properly in the future. Another problem is the lack of uniform criteria and calculation formula regarding the flux of water vapor emitted from the pool water surface. It determines the value of the ventilation air volume flow rate adopted by designers which has an impact on the investment costs resulting from the dimensioning of the ventilation system (size of ventilation ducts, supply and exhaust fans and air handling unit), as well as operating costs related to energy consumption for ventilation air treatment and air transport.

While reviewing the state of knowledge in the field of research on moisture emission from the pool water surface, it was found that the literature contains many formulas for calculating its value, among which there are those derived from the research [3,5,6,25,27,29]. Some of these calculation formulas are constantly being improved by researchers as further experimental research is carried out. For example, in [26] an improved model for calculating water evaporation from pool water surface was presented. Many other researchers also examined this matter. The results of their research were published, among others in [2, 12, 13, 14, 20, 21, 22, 23,24,28].

The paper [7] deals comprehensively with the issues of swimming pool ventilation, including the impact of the selection of calculation formula for moisture emission on the value of the ventilation air volume flow rate and, as a result, the distribution of thermal-moisture and airflow conditions. The results of experimental research carried out in the actual indoor swimming pool were presented in [8, 9]. They were used to assess the indoor air conditions in the examined facility and as boundary conditions for the development and validation of the numerical model of the swimming pool, which was presented in [10].

Research problem

In indoor swimming pools the constant airflow ventilation CAV is usually used. Therefore, the air volume flow rate is calculated for the summer period and its value is maintained throughout the year, regardless of outdoor conditions.

Since the main task of the swimming pool ventilation in summer is to remove excess moisture, the supply air volume flow rate $\dot{V}_N$ is calculated from the formula [16]:

$$\dot{V}_N = \frac{\dot{W}}{\rho_N \cdot \Delta x} = \frac{\dot{W}}{\rho_N \cdot \left(x_i - x_N\right)} \qquad (1)$$

The total mass flux of emitted moisture $\dot{W}$ is the sum of the mass flux of moisture emitted from the surface of pool water $\dot{m}_w$ and wet floors $\dot{m}_p$.

The phenomenon of moisture evaporation from the pool water surface is associated with the so-called boundary layer. It is a layer of minimal thickness that is formed on the border of the contact between the indoor air and the pool water surface. This layer of air is 100% saturated with water vapor, and its temperature is approximately equal to that of the water surface. Emission of moisture from the water surface takes place when the partial pressure of water vapor in the air is lower than its value in the boundary layer. The intensity of the evaporation process is influenced by the difference in water vapor pressure in the boundary layer and in the air. As this difference increases, so does the emission of moisture from the water surface. Increased moisture gains are the result of the boundary layer disturbance caused by the number of swimmers, the air speed above the water surface and the circulation of the pool water.

As in the case of air parameters in the swimming pool, there is no unanimity among researchers on how to calculate moisture emission from the pool water surface. The value of its mass flux can be determined using a number of dependences of experimental origin available in the literature. The authors of these dependencies validate them in their publications using the available results of experimental research.

Table 1 presents selected calculation formulas for the emission of moisture from the pool water surface. One of the basic dependencies is the Carrier formula [6]. It takes into account the surface of pool water, air speed above it, the latent heat of water at the pool water temperature and the difference of partial pressure of water vapor in the boundary layer (in saturated state and at the water surface temperature) and in the indoor air. Smith et al. [27] and ASHRAE [3] formulas are based on the Carrier's. Smith et al. multiplied the Carrier formula by 0.73. ASHRAE, on the other hand, introduced an activity coefficient, the value of which depends on the degree of use of the pool. The formula given in the VDI guidelines [29] introduces the evaporation factor, the value of which depends on the state of the water surface. In the Biasin and Krumme formula [5] there are three experimental coefficients, while Shah [25] makes the emission of moisture dependent on differences in air density and specific air humidity in the boundary layer and in the facility.

An important problem in determining the value of moisture gains from the surface of wet floors is their evaporation surface which changes due to the various number of swimmers and the frequency with which they leave the pool basin. It also depends on the floor temperature, which should not exceed 33°C [15]. This phenomenon is not widely discussed in the literature. Only in some publications the formula for calculating the flux of moisture

Tab. 1. Selected formulas to calculate the moisture emission from the pool water surface

Tab. 1. Wybrane zależności na obliczenie emisji wilgoci z lustra wody basenowej

Source	Formula	Notes	Formula number
acc. to [6]	$\dot{m}_w = \frac{F}{r} \cdot (0{,}0888 + 0{,}0783 \cdot v) \cdot (p_w - p_i)$	constants: 0.0888 W/(m^{2}Pa) 0.0783 (Ws)/(m^{3}Pa)	(2)
acc. to [27]	$\dot{m}_w = 0{,}73 \cdot \frac{F}{r} \cdot (0{,}0888 + 0{,}0783 \cdot v) \cdot (p_w - p_i)$		(3)
acc. to [3]	$\dot{m}_w = \frac{F}{r} \cdot (0{,}089 + 0{,}0782 \cdot v) \cdot (p_w - p_i) \cdot F_a$ If $r \approx 2400$ kJ/kg and $v = 0.05 \div 0.15$ m/s then the equation can be reduced to the form: $\dot{m}_w = 4 \cdot 10^{-5} \cdot F \cdot (p_w - p_i) \cdot F_a$	$F_a = 0.5$ – activity coefficient for an unoccupied pool	(4) (4a)
acc. to [29]	$\dot{m}_w = F \cdot B \cdot (p_w - p_i) \cdot 3600$	Evaporation rate, g/(m^{2}hhPa): – at a calm water surface $B = 5$, – at a normal activity of swimmers $B = 20$	(5)
acc. to [5]	$\dot{m}_w = F \cdot \left[-0{,}059 \frac{0{,}0105 \cdot (p_w - p_i)}{133{,}3} \right] \cdot 3600$	-0.059; 0.0105; 133.3 – experimental coefficients	(6)
acc. to [25]	$\dot{m}_w = F \cdot C \cdot \rho_w \cdot (p_i - p_w)^{1/3} \cdot (x_w - x_i) \cdot 3600$ If the expression $(\rho - \rho_w) < 0$ then its absolute value is assumed.	$C = 35$ for $(\rho_a - \rho_w) > 0.02$ $C = 40$ for $(\rho_a - \rho_w) < 0.02$	(7)

evaporating from wet unheated floors can be found [4,18,19]:

$$\dot{m}_p = a \cdot (t_i - t_m) \cdot F_p \qquad (8)$$

The value of the coefficient of evaporation from the floor surface *a* depends on the author's recommendations, e.g. Malicki proposes to assume a = 0.006 kg/(m^2·h·°C).

In [12,21,22] it was pointed out that the calculations of moisture emission from the pool water surface using different formulas available in the literature give very divergent results, what causes problems in the design of swimming pools ventilation system. The adoption of various formulas in the process of determination the value of the ventilation air volume flow rate and dimensioning of the ventilation system could result in even several-fold differences in investment costs [21].

In [7,11] during the preliminary numerical calculations of ventilation air distribution modeling in the swimming pool, carried out in Ansys CFX software [1], a problem was encountered with the correct mapping of thermal-moisture and airflow conditions regarding the calculation formula for the emission of moisture from the pool water surface. Therefore, in the main numerical research, the distribution of air parameters in the facility was modeled by implementing into the software various calculation formulas for the moisture emission from the pool water surface, given in Table 1 [3,5,6,25,27,29]. On the basis of a comparison of the distribution of air parameters obtained from experimental research [8,9] and numerical calculations [7,10], the calculation formula was selected, which was then used to calculate the ventilation air volume flow rate and for further research. As a result of this research, an experimental-numerical method of selecting the model of moisture emission from the pool water surface, presented in this paper, was validated. This method is utilitarian and can be used to modernize ventilation systems in the existing swimming pools in order to improve the thermal-moisture conditions for the occupants and maintaining a good technical condition of the facility.

Tested facility and its numerical model

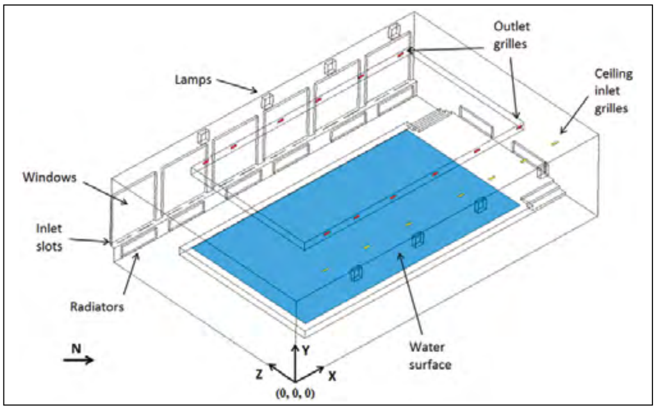
The tested facility was the actual school swimming pool of the Primary School no. 28 in Gliwice, with dimensions: length 17.6 m, width 11.7 m, average height 4.4 m. The dimensions of the pool basin were: length 12.5 m, width 7 m, depth 1.36 m. The pool basin was surrounded by 40 cm-high wall, therefore the water surface was 40 cm above the floor level, which surrounded the pool basin. The swimming pool was equipped with a mixing ventilation system with one-sided, under-window air supply. In order to ensure adequate air circulation in the occupied zone, at the exit from the locker room, a ceiling air supply was provided over this part of the floor. The air was exhausted under the ceiling of the facility. The ventilation system operated in a continuous operation mode, supplying the constant flow of ventilation air around the clock. The main component of the system was the air handling unit located in the room connecting the school building with the swimming pool.

A detailed description of the facility and its ventilation system as well as the use of the swimming pool were presented in [8, 9]. They encompassed the course and results of experimental research carried out in order to assess the thermal-humidity and airflow conditions in the examined swimming pool, as well as those necessary for thermal diagnostics of the facility. The aim of the experimental research was also to collect data for boundary conditions of numerical modeling, as well as for the improvement and experimental validation of the air distribution numerical model.

Numerical modeling CFD applied in the research on ventilation of various facilities, including the swimming pool, can be very useful for analyzing the distribution of thermal-moisture and airflow parameters in buildings, as presented in [17].

In the research of the swimming pool, numerical calculations were carried out with the use of Ansys CFX 14.5 [1] software, in which the numerical model of the examined facility was prepared (Fig. 1). It took into account the actual dimensions and geometry of the building and the pool water surface. Ventilation air distribution, heating and lighting systems were modeled, as well. The water surface was modeled as a surface of fixed temperature. A flux of emitted moisture

Fig. 1. Numerical model of the examined swimming pool
Rys. 1. Model numeryczny badanej hali pływalni



Tab. 2. The boundary conditions for the examined indoor swimming pool for all the measurement cases
Tab. 2. Warunki brzegowe dla badanej hali pływalni dla wszystkich serii pomiarowych

Boundary conditions	Unit	Case 1	Case 2	Case 3
Mass flow rate of air supplied by the ceiling inlet grilles	kg/s	0.369	0.306	0.475
Mass flow rate of air supplied by the inlet slots	kg/s	0.155	0.128	0.321
Mass flow rate of exhaust air = total mass flow rate of supply air	kg/s	0.524	0.434	0.796
Outdoor air temperature	°C	28.2	27	28.3
Supply air temperature	°C	1.5	23.9	2.5
Temperature of water in the swimming pool's basin	°C	29.9	28.2	29.9
Specific humidity of supply air	kg H_2O/kg d.a.	0.00362	0.00843	0.00325
Mass flux of emitted moisture from the surface of the water	kg/s	0.00200	0.00161	0.00234
Mass flux of emitted moisture from the wet floor	kg/s	0.00026	0.00021	0.00047
Heat flux from a single lighting fixture	W/m^2	Radiation		
		395.2	-	-
		Convection		
		592.8	-	-
Heat flux from a single radiator	W/m^2	Radiation		
		462.8	-	462.8
		Convection		
		694.2	-	694.2
Heat transfer coefficient of the north-west wall	W/(m^{2}K)	0.223		
Heat transfer coefficient of the south-west wall	W/(m^{2}K)	0.340		
Heat transfer coefficient of a window in the south-west wall	W/(m^{2}K)	1.522		

was applied to that surface, according to formulas (2) to (7).

The boundary conditions for numerical calculations were developed on the basis of the results of experimental identification obtained as part of short-term measurements carried out in three measurement cases: in spring – case 1, in summer – case 2 and in winter – case 3 [8,9] and on the basis of the building documentation. They encompassed mean or time-averaged measurement values of the following parameters: air mass flux, temperature and specific humidity of supply air, temperature and specific humidity of external air, water surface temperature, mass flux of moisture evaporating from the water surface and wet floors, heat fluxes from lighting and radiators as well as heat transfer coefficients of building partitions. Table 2 presents the boundary conditions for the examined swimming pool, which were used for numerical calculations.

The numerical calculations were carried out under steady, non-isothermal conditions. For the discretization of the differential equations of the system, the Finite Volume Method (FVM) was used. The second-order upwind discretization scheme implemented in the Ansys CFX software and the Rhie Chow algorithm for the pressure and speed coupling were used. The SST (Shear Stress Transport) turbulence model from the EVM (Eddy-Viscosity Models) group was applied in the research. Modeling of thermal radiation between the partitions, the water surface and the equipment inside the swimming pool was carried out using the Discrete Transfer Model (DTM).

Before carrying out the main numerical calculations it was necessary to determine the parameters of the discretization grid used for simulations. Three discretization grids composed of unstructured, mainly tetrahedral elements were tested in the course of preliminary numerical calculations carried out for the boundary conditions from the measurement case 1. Test results were validated by comparing the mean values of speed, temperature, relative humidity and specific humidity of the air in the zone around the pool basin at each measurement height: 0.1 m, 0.6 m, 1.1 m. 1.7 m, as well as above the pool water surface, with the values measured in the occupied zone in the actual facility. The best convergence of the results was obtained for the discretization grid, in which the grid cells were refined on the surface of the inlets and outlets (and in their vicinity), as well as up to 0.2 m above the water surface, i.e. at the head of the swimmer. The length of mesh cell edge was 0.1 m, and in the places of refinement, respectively: 0.01 m on the surface of inlets and outlets, and 0.05 m above the water surface. Table 3 presents the mean values of air parameters above the pool water surface obtained from measurements and numerical calculations for the selected discretization grid, shown in Fig. 2.

Tab. 3. Comparison of mean values of the experimental and numerical parameters at a height of 0.2 m above the water surface for the selected discretization grid
Tab. 3. Porównanie średnich wartości parametrów eksperymentalnych z numerycznymi na wysokości 0,2 m nad lustrem wody dla wybranej siatki dyskretyzacji

Air parameter	Unit	Measurement	Numerical calculation
Speed	m/s	0.12 ± 0.02	0.08
Temperature	°C	27.3 ± 0.2	26.8
Relative humidity	%	54.6 ± 3	52.3
Specific humidity	kg H_2O/kg d.a.	0.0124 ± 0.0008	0.0129

Fig. 2.
View of the selected discretization grid in the plane *X* = 4.2 m
Rys. 2. Widok wybranej siatki dyskretyzacji w płaszczyźnie X = 4,2 m

Numerical modeling of moisture emission from the pool water surface using the experiment

In order to use the developed numerical model of the swimming pool to calculate various variants of air distribution in such a facility, it had to be validated using the results of experimental identification of air parameters distribution in the actual facility [8,9]. The validation of the numerical model was divided into two stages [7]:

1. development and improvement of the numerical model by selecting the most accurate method of moisture emission modeling,
2. experimental validation of the results of numerical calculations carried out with the use of the improved model.

During numerical modeling of the swimming pool [7], the pool water was treated as a source of heat and moisture, for which values of water temperature and moisture gains were set. Moisture gains were determined using formulas (2) – (7), presented in Table 1. Since their calculation required the knowledge of the values of the air parameters in the facility in the immediate vicinity of the water surface, at the stage of model preparation, they could only be estimated, which did not ensure an accurate mapping of moisture emission. This method of applying moisture gains resulted in inaccurate mapping of thermal-moisture phenomena in the facility and led to discrepancies between the results of numerical calculations and the actual values of air parameters [11].

Therefore, in the main research, a method of modeling moisture emission in the swimming pool was proposed. It consisted in the implementation into the Ansys CFX software calculation formulas (2) – (7) to which the actual values of air and water parameters obtained from measurements were applied [8,9]. These formulas required values of such parameters as: water evaporation heat *r*, partial pressure of water vapor at saturation and water surface temperature p_w, and partial pressure of water vapor at air temperature and indoor humidity p_a, calculated on the basis of numerical values of temperature and moisture content in the air above the water surface.

After implementing the formulas, the Ansys CFX software calculated in real state the values of these parameters, and as a result, the value of moisture emission from the water surface in individual nodes of the discretization grid above the water.

Numerical calculations were carried out for all the formulas presented in Table 1, for the boundary conditions corresponding to the measurement case 1. The results of numerical simulations were then validated with the results of measurements, including values of air temperature, speed, relative humidity and specific humidity.

In fig. 3 the maps of specific air humidity in the *Y* = 0.6 m plane (passing at a height of 0.2 m above the water surface), created on the basis of the experimental and numerical results were compared. On these maps, the area with specific air humidity values exceeding the limit value of 0.016 kg H_2O/kg d.a. was marked in red, according to the sultriness curve. This area varied greatly depending on the calculation formula. As a result of applying the Carrier formula, the limit value was exceeded almost in the entire plane *Y* = 0.6 m (by 2.5% to 17.5%). For Smith et al.'s formula, this area covered only about

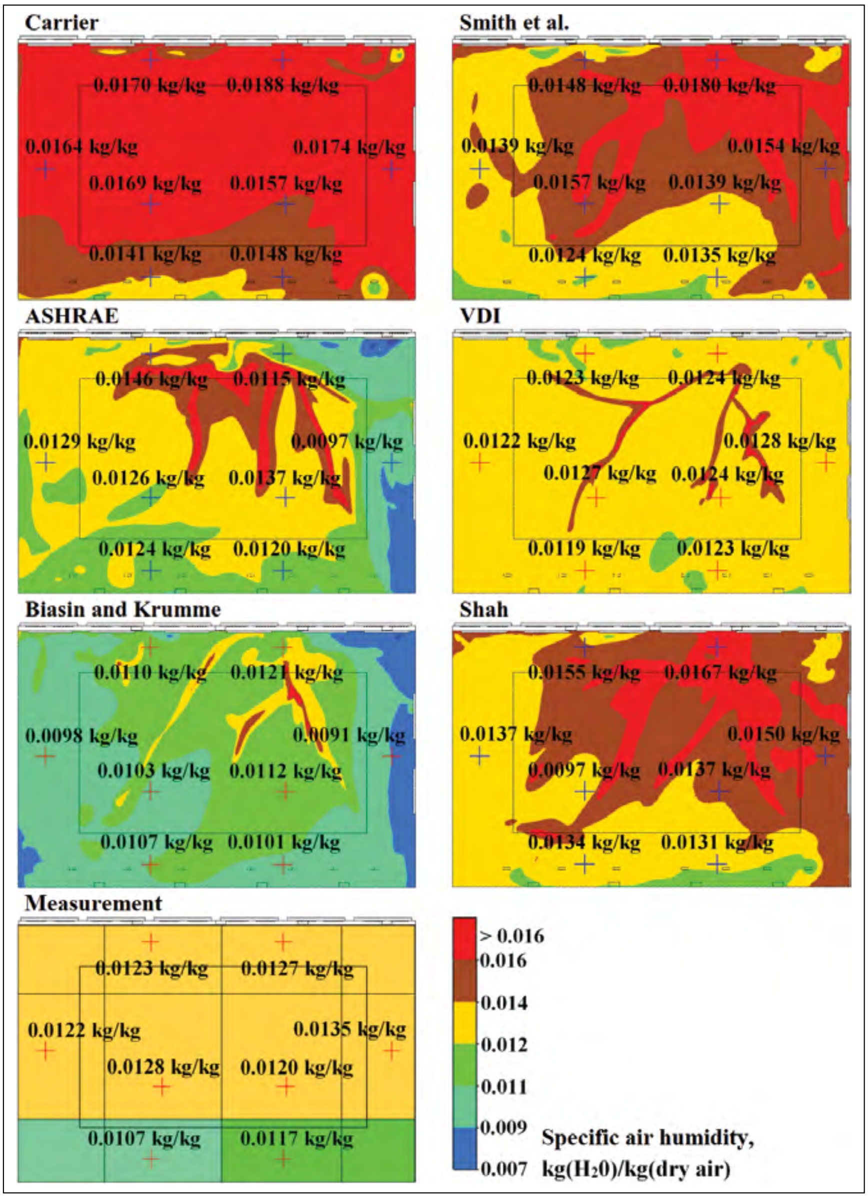


Fig. 3.
Distribution of specific air humidity in the plane *Y* = 0.6 m for the calculation formulas for the emission of moisture from the pool water surface (2) – (7) and measurements (measurement case 1) [10]
Rys. 3. Rozkład wilgotności właściwej powietrza w płaszczyźnie Y = 0,6 m dla formuł obliczeniowych (2) – (7) na emisję wilgoci z lustra wody basenowej i pomiarów (seria pomiarowa 1) [10]

1/3 of the plane, and in the case of Shah and ASHRAE formulas it was even smaller. On the other hand, when the VDI and the Biasin and Krumme formulas were applied, the values exceeding the limit one occurred only locally. It is noteworthy that the measurement value exceeding the limit one did not occur at any measurement point. The comparison of all the results of measurements and numerical calculations showed that the highest values of specific air humidity were obtained for the Carrier formula, 26.5% to 48% higher than the measurement ones. For Smith et al. formula, the values of this parameter were higher than the measurement ones by 13.9% to 41.7%, for the Shah formula they differed from the measurement ones by – 24.2% to 31.5%, and for the ASHRAE formula by – 28.1% to 24.4%. The application of the Biasin and Krumme formula contributed to the distribution of the lowest values of the parameter, even 32.6% lower than the measured ones. As a result, the values for the Biasin and Krumme formula were too low, and for the Carrier, Smith et al. and Shah formulas too high compared to the measurements. The distribution of specific air humidity closest to the measurement one was obtained using the VDI formula. Most of the numerical values of the specific humidity of the air were consistent with the measurements or were within the limits of the measurement error, and only locally values slightly lower or higher than the measurement ones occurred.

A detailed comparison of other air parameters distribution in the swimming pool obtained from measurements and numerical calculations at all measurement points is not presented in this paper, as from the point of view of using the validated model for further numerical analyzes their mean values in occupied zone were important. Table 4 presents the mean values of air parameters above the water surface, determined on the basis of the numerical calculations and measurements.

In the case of the values above the water surface, the air temperature range was from 27.2°C for the VDI formula to 28.5°C for the Shah formula, while the measured value equaled 27.3°C. The relative discrepancy between the numerical value and the measured one was in the range of – 0.4% to 4.4%. Full compliance with the measurement result was obtained for the Biasin and Krumme formula.

The range of air speed above the water surface was from 0.07 m/s for the Biasin and Krumme formula to 0.16 m/s for the Carrier formula. The value obtained from the measurements was 0.12 m/s. The relative discrepancy between the numerical value and the measured one ranged from – 41.7% to 33.3%. Total compliance with the measurement result was obtained for the ASHRAE formula.

In the case of air relative humidity, the values above the water surface ranged from 37.9% for the Biasin and Krumme formula to 55.8% for the Carrier formula. The value obtained from the measurements was 54.6%. The relative discrepancy between the numerical value and the

Tab. 4. Comparison of mean values of air parameters for measurements and numerical simulation results at measurement points above the water surface for the tested models of moisture emission from the pool water surface for measurement case 1
Tab. 4. Porównanie średnich wartości parametrów powietrza dla pomiarów i wyników symulacji numerycznych z punktów pomiarowych nad lustrem wody dla badanych modeli emisji wilgoci z lustra wody w niecce basenowej dla serii pomiarowej 1

Air parameter	Measurement	Model of moisture emission from the pool water surface					
		ASHRAE	Biasin & Krumme	Carrier	Shah	Smith et al.	VDI
Temperature, °C	27.3 ± 0.2	27.4	27.3	27.8	28.5	27.8	27.2
Speed, m/s	0.12 ± 0.02	0.12	0.07	0.16	0.14	0.10	0.08
Relative humidity, %	54.6 ± 3	46.2	37.9	55.8	38.8	50.7	55.6
Specific humidity, kg H_2O/kg d.a.	0.0124 ± 0.0008	0.0131	0.0107	0.0163	0.0117	0.0148	0.0126

measured one ranged from – 30.2% to 2.2%. The highest compliance with the measurement result was obtained for the VDI formula, which amounted to 55.6% and thus it differed by 1.8% from the measured value.

The range of the value of specific air humidity above the water surface was from 0.0107 kg H_2O/kg d.a. for the Biasin and Krumme formula up to 0.0163 kg H_2O/kg d.a. for the Carrier formula, while the measured value was 0.0124 kg H_2O/kg d.a. The relative discrepancy between the numerical value and the measured one ranged from – 13.7% to 31.5%. The best compliance with the measurement result was obtained for the VDI formula, which was 0.0126 kg H_2O/kg d.a. and thus it differed by 1.6% from the measured value.

To sum up, it should be stated that the selection of the appropriate calculation formula for the emission of moisture from the pool water surface had an impact on the values of all air parameters in the facility, although, it concerned the specific air humidity to the greatest extent. The best compliance of numerical and measurement results for this parameter was obtained for the VDI formula. With the use of it, in the horizontal plane $Y = 0.6$ m, a very high convergence of the distribution of this parameter with the measured one was obtained, both above the floor around the pool basin and above the water surface. Comparing the values of air parameters in the measurement axes above the floor around the pool basin at different heights (0.1 m, 0.6 m, 1.1 m and 1.7 m), it was found that the highest overstating of the specific air humidity value, up to +48% of the measurement one, was obtained for the Carrier formula, and the greatest understating of the value, reaching – 32.6%, was obtained for the Biasin and Krumme formula. Similar observations apply to air temperature and relative humidity, for which the values closest to the measurement ones were obtained using the VDI formula. Therefore, in further numerical calculations, the VDI formula was used to calculate moisture emission from the pool water surface.

Experimental validation of the numerical model

The goal of experimental validation was to assess whether the developed and improved numerical model of air, heat and moisture flow in the swimming pool simulated the occurring physical phenomena well and therefore could be used for further research. The numerical calculations were carried out with the use of the VDI moisture emission model for the boundary conditions presented in Table 2 and their results were validated with the use of measurements.

A detailed comparison of the results of numerical simulations with the results of measurements of indoor air parameters, i.e. temperature, speed, relative humidity and specific humidity in six measurement axes in the area around the pool basin and in two measurement points above the water surface was carried out for one selected measurement case (case 1). Fig. 4 shows this comparison in the form of air parameters distribution maps in the horizontal plane at a height of 0.6 m above the floor (0.2 m above the water surface). It was found that both the distribution and the values of air temperature, relative humidity and specific humidity obtained from numerical simulations largely coincided with the measurement values above the floor around the pool basin and above the water surface. The greatest differences were observed in the case of air speed (Fig. 4b), the simulated values of which at all measurement points were lower than the measurement ones.

Relative discrepancies between the values of measurements and numerical calculations were also analyzed (Fig. 5). The greatest difference occurred in the case of air speed, for which the probability of the occurrence of a relative discrepancy of 50% was the lowest at the heights of 0.1 m and 1.7 m above the floor and amounted to 17%. For the remaining air parameters

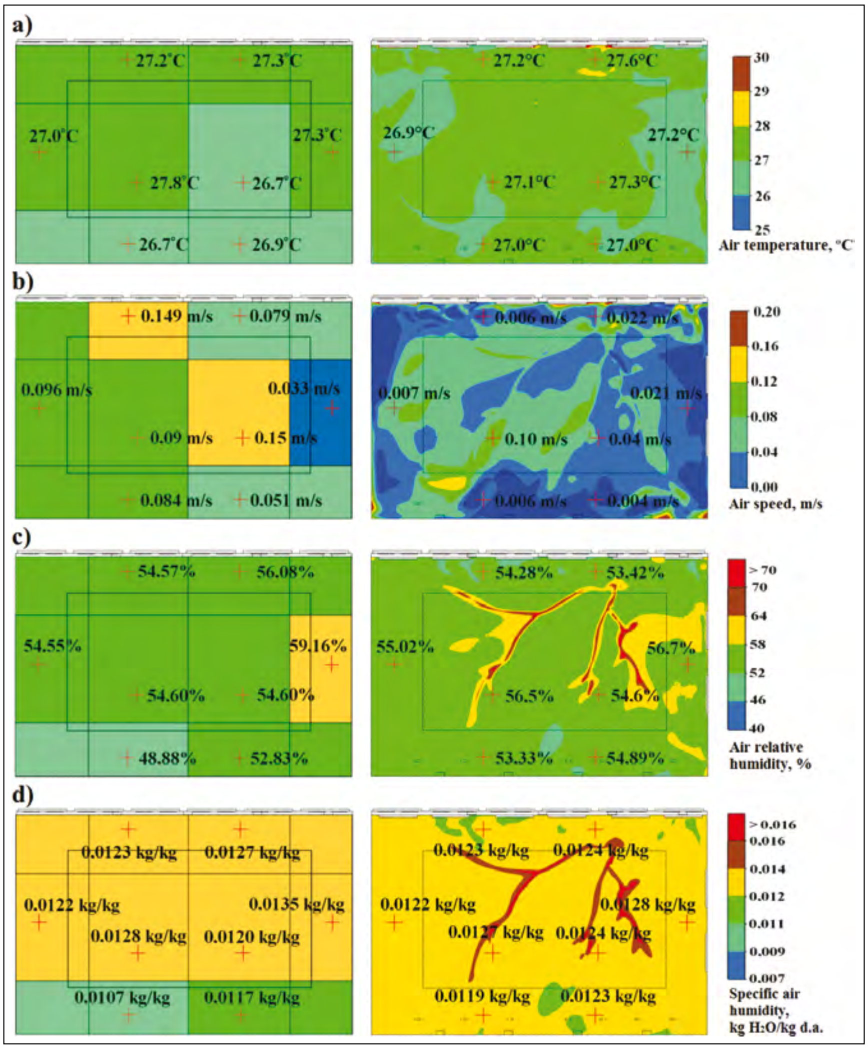


Fig. 4.

Comparison of the results of numerical simulations (on the right) with the results of measurements in the swimming pool (on the left) for: a) air temperature, b) air speed, c) air relative humidity, d) specific air humidity, at a height of 0.6 m above the floor around the pool basin and 0.2 m above the water surface for the measurement case 1

Rys. 4. Porównanie wyników symulacji numerycznych (po prawej) z wynikami pomiarów w hali pływalni (po lewej) dla: a) temperatury, b) szybkości, c) wilgotności względnej, d) wilgotności właściwej powietrza, na wysokościach 0,6 m nad posadzką wokół niecki basenowej i 0,2 m nad lustrem wody dla serii pomiarowej 1

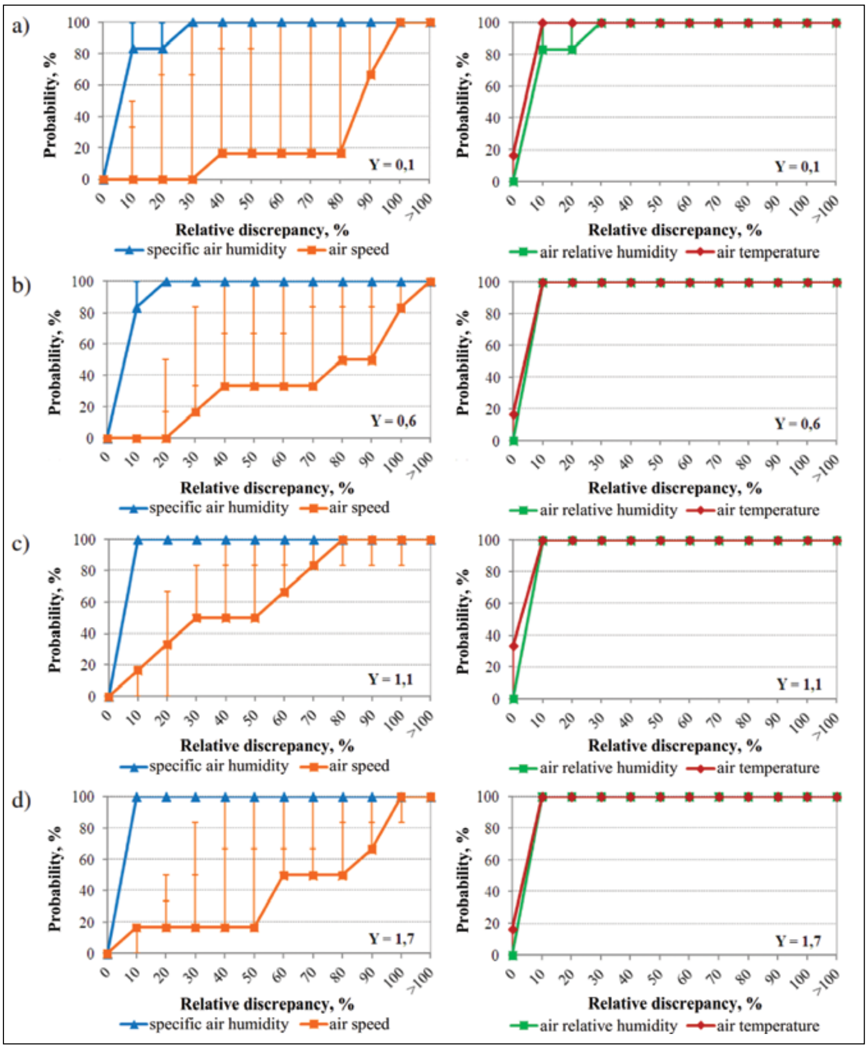


Fig. 5.
The probability of occurrence of relative discrepancies between the results of numerical simulations and measurements of air temperature, speed, relative and specific humidity in six measurement axes at the heights of a) 0.1 m, b) 0.6 m, c) 1.1 m, d) 1.7 m above the floor (measurement case 1)
Rys. 5. Prawdopodobieństwo występowania względnych rozbieżności pomiędzy wynikami symulacji numerycznych oraz pomiarów temperatury, szybkości, wilgotności względnej i właściwej w sześciu osiach pomiarowych dla wysokości a) 0,1 m, b) 0,6 m, c) 1,1 m, d) 1,7 m nad posadzką (seria pomiarowa 1)

Tab. 5. Comparison of the results of experimental measurements with the results of numerical simulations at a height of 0.2 m above the water surface for all measurement cases
Tab. 5. Porównanie wyników badań eksperymentalnych z wynikami symulacji numerycznych na wysokości 0,2 m nad lustrem wody dla wszystkich serii pomiarowych

Measurement case	Measured mean value	Numerical mean value	Measured mean value	Numerical mean value
	Air speed, m/s		Air temperature, °C	
Case 1	0.12 ± 0.02	0.08	27.3 ± 0.2	27.2
Case 2	0.15 ± 0.02	0.09	25.7 ± 0.2	25.9
Case 3	0.19 ± 0.02	0.15	27.8 ± 0.2	27.1
Measurement case	Air relative humidity, %		Specific air humidity, kg H_2O/kg d.a.	
Case 1	54.6 ± 3	55.6	0.0124 ± 0.0008	0.0126
Case 2	63.9 ± 3	67.0	0.0132 ± 0.0008	0.0141
Case 3	49.3 ± 3	46.9	0.0115 ± 0.0008	0.0105

more convergent values were obtained. For air temperature, the probability of a relative discrepancy of no more than 10% was 100%. In the case of air relative humidity, the probability of a relative discrepancy of no more than 10% was 100% at heights of 0.6 m, 1.1 m and 1.7 m and no more than 30% was 100% at a height of 0.1 m. The same was true for the specific air humidity, with the difference that the probability of a relative discrepancy of no more than 20% was 100% at a height of 0.6 m. The probability of a relative error not exceeding 50% for all air parameters at each of the analyzed heights was within the range from 17% to 100%.

Additionally, mean values of air parameters at measurement points at a height of 0.2 m above the pool water surface for all measurement cases were analyzed (Table 5). The numerical values of air speed for measurement cases 1 and 3 were within the measurement error range, while for measurement case 2 they differed from it by 0.04 m/s. Air temperature values were within the error limits for measurement cases 1 and 2, and for case 3 they differed from it by 0.5°C. The numerical values of air relative humidity for measurement cases 1 and 3 were within the measurement error range, and for case 2 they deviated from it only by 0.1%. Equally small differences occurred in the matter of specific air humidity, the calculation values of which for cases 2 and 3 differed from the measurement error range, respectively, by 0.0001 kg H_2O/kg d.a. and 0.0002 kg H_2O/kg d.a., and for the case 1 were within this range.

Summing up the experimental validation of the numerical simulations results for three measurement cases, it was found that a good mapping of air parameters was obtained both above the floor around the pool basin and above the pool water surface. In the case of air relative humidity and specific air humidity, the numerical values were largely consistent with the measurement ones for each measurement case at each height. In the matter of air temperature, at points in which the measurement values were not obtained, the average difference between the numerical results and the range of the measurement error was small and amounted to 0.3°C. In the matter of air speed, in most of the measurement cases, a high convergence with the measurement results was also obtained, except for the height of 0.1 m, which was due to the specific location of this measurement point.

Conclusions

On the basis of the conducted research, presented in chapters 3 to 5, it was proved that the numerical prediction of thermal-moisture and airflow conditions in the indoor swimming pool was influenced by the calculation formula for the emission of moisture from the pool water surface.

The model of moisture emission based on the VDI formula (5) turned out to be the most accurate among those presented in

Table 1. It provided the best convergence of air parameters distribution obtained from measurements and numerical calculations above the floor around the pool basin and the water surface.

Taking into account the high convergence of the numerical results with the measurement ones, it was found that the numerical model of the examined swimming pool enabled a good mapping of the actual conditions and most of the phenomena related to the flow of air, heat and moisture. In the case of air temperature, the probability of a discrepancy of no more than 10% was 100%, for air relative humidity – 96%, for specific air humidity – 92%, and for air speed – 8%. This means that the developed numerical model could be used for further research on the ventilation of the swimming pool.

As part of the experimental research and numerical calculations concerning the modeling of ventilation air distribution in the swimming pool, described in this paper and presented in [7,8,9,10], utilitarian research method was developed and validated for the selection of the model of moisture emission from the pool water surface. It encompasses the following steps:

1. review and selection of literature calculation formulas for the emission of moisture from the pool water surface,
2. carrying out an experimental identification of the thermal-moisture and airflow conditions in the actual swimming pool (air temperature, humidity and speed measurements) – necessary to determine the boundary conditions for numerical tests and the values of air and water parameters in the calculation formulas,
3. implementation of theses formulas, including the actual measurement values of air and water parameters, in a numerical software – as a result, the numerical program is able to calculate the value of moisture emission from the water surface in each node of the computational grid above the water surface,
4. validation of the numerical distribution of air parameters above the water surface and around the pool basin by comparing it with the measurement results – on this basis, the most reliable model for the emission of moisture from the pool water surface, which makes it possible to obtain the temperature, humidity and airflow conditions closest to the actual state, can be determined.

Setting fixed value of moisture gains without carrying out an experimental identification of air and water parameters may result in inaccurate mapping of indoor air parameters and lead to discrepancies between the results of numerical calculations and actual thermal-moisture conditions in the facility. Therefore, this method can be recommended when the ventilation system in the existing indoor swimming pool needs to be modernized to improve thermal-moisture conditions in the facility.

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