ASSESSMENT OF THERMAL COMFORT IN AN INDOOR SWIMMING-POOL MAKING USE OF THE NUMERICAL PREDICTION CFD

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A b s t r a c t

The paper suggests a way of assessing the conditions of thermal comfort existing in the occupied zone, which would permit to compare explicitly various concepts of the air distribution in a ventilated room. This way is based on results of the CFD numerical prediction of the air parameters, as well as on methods of assessing thermal comfort, applied up to now, such as Lancaster-Castens-Ruge's sultriness curve, Predicted Mean Vote *PMV*, Predicted Percentage of Dissatisfied *PPD*, Draught Rate *DR*, Air Diffusion Performance Index *ADPI*. The paper presents the idea and practical realisation of this way on the example of an indoor swimming- pool, whose numerical model was worked out using the CFD code CFX Ansys. The required ranges of the values of the criteria assessing thermal comfort in the occupied zone of such objects were given. This suggested way consists in determining the percentage of the area of the plane in the occupied zone at a adequate selected height where these criteria are satisfied, using for this purpose numerically predicted air parameters. Exemplary results of such assessment for investigated indoor swimming-pool were presented. Futher possibility of a practical use of the suggested way was indicated.

S t r e s z c z e n i e

W artykule zaproponowano sposób oceny warunków komfortu cieplnego w strefie przebywania ludzi, który pozwala na jednoznaczne porównanie różnych koncepcji rozdziału powietrza w pomieszczeniu wentylowanym. Sposób ten bazuje na wynikach prognoz numerycznych metodą CFD parametrów powietrza oraz na metodach oceny komfortu cieplnego, stosowanych dotąd, takich jak: krzywa duszności wg Lancastera-Cartensa-Ruge, Przewidywanej Ocenie Średniej *PMV* i Przewidywanym Odsetku Niezadowolonych *PPD*, wskaźniku Ryzyka Przeciągu *DR* oraz wskaźniku *ADPI*. W artykule pokazano ideę i praktyczną realizację tego sposobu na przykładzie hali pływalni, której model numeryczny został opracowany za pomocą programu CFD CFX Ansys. Podano wymagane zakresy wartości parametrów i kryteriów oceny komfortu cieplnego w strefie przebywania ludzi w takich halach. Zaproponowany sposób polega na określeniu procentowego udziału pola powierzchni płaszczyzny na odpowiednio wybranej wysokości w strefie przebywania ludzi, gdzie wspomniane kryteria były spełnione, przy wykorzystaniu do tego celu prognozowanych numerycznie wartości parametrów powietrza. Pokazano przykładowe wyniki takiej oceny dla badanej pływalni. Wskazano dalsze możliwości praktycznego zastosowania proponowanego sposobu.

K e y w o r d s: **Indoor swimming-pool; Ventilation; Air distribution; Thermal comfort; Numerical calculation CFD.**

1. INTRODUCTION

The choice of the adequate concept of ventilation air distribution is one of the most important states in designing ventilation or air-conditioning. Of much use is for that purpose the application of numerical prediction of the airflow inside any enclosure by means of the CFD method, which permits to obtain information about predicted distribution of air parameters, e.g. in the occupied zone, already in the course of designing.

The best choice – from the viewpoint of obtained conditions of thermal comfort – is achieved by comparing effects of application of different variants of ventilation air distribution. So far, for this purpose qualitative comparison of parameter map was applied, or the values of lumped parameters in the occupied zone were compared, e.g. the value of mean, maximum and minimum parameters [1], [2], [3].

Provided information was, however, rather scarce and does not allow to assess comprehensively these concepts of ventilation air distribution.

The present paper suggests a way of assessing conditions existing in the occupied zone, which would permit explicit comparison of various concepts of air distribution in a ventilated room numerically. This way is based on the results of numerical prediction of air parameters, as well as on methods of assessing conditions of thermal comfort, applied up to now. The paper presents the idea and practical realisation of this way on the example of an indoor swimming- pool

2. THERMAL CONTROL IN INDOOR SWIMMING-POOL AND METHODS OF THEIR ASSESSMENT

The conditions of thermal comfort require in roofed swimming-pools are connected with the character and use of such facilities, kept in mind the people abiding there are scarcely dressed. There are, however, no very strict requirements concerning the parameters of the microclimate in such a hall, although a considerable connection between the respective parameters of the air is to be observed. The air temperature t ought to be about (2-4) K higher than water temperature, generally it is assumed to amount between 28-32°C. Too high temperature evokes the feeling of lassitude, because human organism exchanges too week heat flux with the ambient air, whereas too low temperature makes people feel cold, as to much heat is given by the wet skin. If the air temperature is being reduced and the relative humidity remains unchanged, the evaporation of water is intensified. Therefore, it is recommended that the air relative humidity φ in indoor swimming-pool should be maintained within the range of 45-65% and specific humidity should not exceed 0.016 kgH_2O/kg p.s.

A lower value of φ is unjustified not only because of human comfort, but also due to economical reasons, because it requires more energy for the dehumidification of the air. Humidity exceeding 65% enhances difficulties in breathing and may lead to a condensation of vapour from the air onto the construction of the hall, particularly in seasons when the outside temperature is low. The air speed v should not exceed 0.2 m/s, because higher values contribute to increased evaporation of water, and thus to a higher air relative humidity, and also to draughts.

Due to all these parameters taken together, affecting the thermal comfort, its assessment should include those criteria which take into account their interdependence. The example of such an approach may be Lancaster-Castens-Ruge's sultriness curve (upper comfort zone limit), presented in Fig. 1, which displays the values of temperature and relative humidity, the excess of which makes people feel phenomena of sultriness.

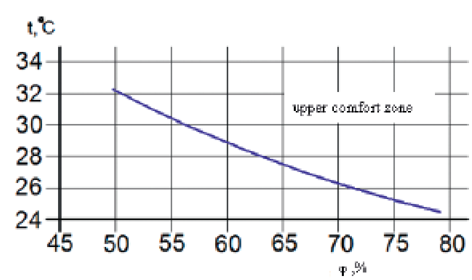

Figure 1.
Lancaster-Castens-Ruge's sultriness curve (upper comfort zone limit) for the indoor swimming pool

To assess thermal comfort in roofed swimming-pool also indices concerning other rooms may be applied. The mutual dependence existing between the air temperature and the speed is expressed by the Air Diffusion Performance Index (*ADPI*) [4], determining the percentage of measuring points in the room in which the criterion:

$$\Theta = t - t_i - 8(\nu - 0.15) \tag{1}$$

is contained within the range -1.7°C<Θ<1.1°C, at ν<0.35 m/s

The Draught Rate *DR* [5] informing about the predicted percentage of those dissatisfied due to the existing draught is determined depending on the local temperature and air speed, and also on the turbulence intensity of the airflow *Tu*:

$$DR = (34 - t_i)\cdot(v_i - 0.05)^{0.62}\cdot(37\cdot Tu v_i + 3.14) \qquad (2)$$

In case of the room with mean requirements (category B), as which indoor swimming-pools were classified, the value $DR=20\%$ must not be exceeded.

All the factors influencing the thermal comfort realized by users of the swimming-pool were taken into consideration in the Predicted Mean Vote (*PMV*) and the respective Predicted Percentage of Dissatisfied (*PPD*). The *PMV* may be more strictly connected with the requirements concerning the thermal comfort in swimming-pools, because besides the value of the air parameters also the mean radiant temperature, parameters of clothing worn by the people and their physical activity are taken into account. The index PMV ought to be contained in the range $<-0.5, 0.5>$, corresponding to PPD $\leq 10\%$.

In all presented methods the conditions of thermal comfort are usually assessed based on measurements, obtained results being provided in the form of air distribution in rooms, which restricts the assessment to selected places or to the mean values in the entire enclosure. There are no objections to use for this purpose distributions of air parameters predicted numerically using method of computational fluid mechanics (CFD). In [2] this was done to get the mean values of the aforesaid criteria of assessment. It is, however, to determine their distribution all over the room or its selected part, which is to be analysed in the further part of this paper.

3. INFORMATION ABOUT THE CFD COMPUTER CODE, APPLIED FOR THE ASSESSMENT OF THERMAL COMFORT IN AN INDOOR SWIMMING-POOL

The distributions of the air parameters in a ventilated enclosure can be determined by means of computer programs based on the CFD technique. One of the worldwide leading code of this type is CFX Ansys (www.ansys.com), applied in the calculations carried out in this paper. This code is based on a set of differential equations describing the fundamental laws of fluid mechanics and heat transfer, averaged in time and solved numerically, making use of the method of controls volumes. To take into account the turbulence of flow, the program suggests various models of turbulence, among others so far most frequently used two-equation models k-ε and SST. These models assign to each node scalar quantities describing the turbulence in the given point. A drawback of this solution is that the direction of the turbulence is not taken into consideration, which may lead to unrealistic results concerning the shearing of the jet. Such a phenomenon occurs when the jet flows into a large unlimited space, which is often the case in ventilation. Six-equation models based on Reynolds stresses prove to be in this case more adequate. They permit to determine turbulence in every direction. A disadvantage, however, is that they require more equations to be solved, which involved the necessity of more time and memory.

A numerical solution is carried out in an unstructural discretization grid, consisting of tetrahedral elements, generated automatically by the subroutine of the CFX code. The grid can be fitted accurately even to geometrical elements of complicated shapes. This program makes it possible to control to a large extent the parameters of the grid (its local refinement and the formation of the boundary layer of hexahedral elements).

An immediate result of the numerical calculation is the matrix of the grid points together with the values of the air parameters, which are from the viewpoint of ventilation of great importance, such as the averaged velocity components, the temperature or the share of the respective components of wet air. A postprocessor facilitates the formation of coloured maps presenting the distribution of the parameters, three dimensional images of the airflow and calculations of numerical data, e.g. of the averaged velocity or temperature. All this will be dealt with in the further part of the paper.

4. CHARACTERISTICS OF THE INVESTIGATED SWIMMING-POOL AND ITS NUMERICAL MODEL

The possibilities of assessing the conditions of the thermal comfort numerically are illustrated on the example of the actual roofed swimming-pool in a school in Bytom (Poland) (Fig. 2a). The dimensions of this hall are: length 95.7 m, width 17.7 m and height 4.2 m and the dimensions of the pool: 7.2 m by 12.5 m. Its northern external wall is provided with windows, the remaining three walls adjoin other rooms. The roof also contacts the air outside. To adapt the model to the investigation, it was slightly

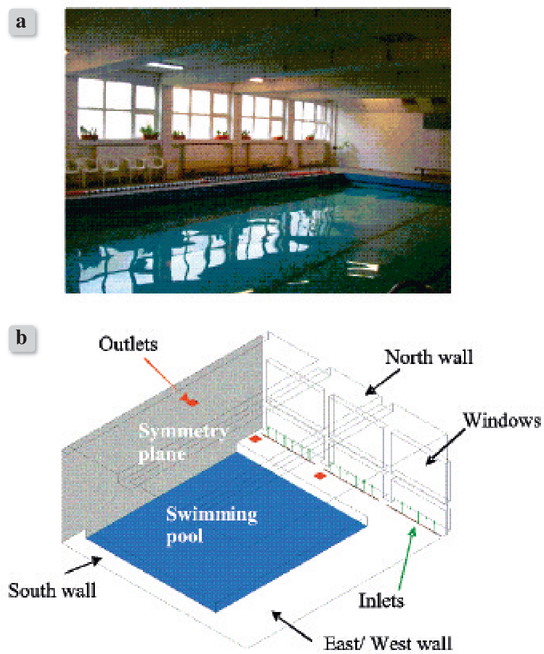

Figure 2.
The hall of the swimming-pool a) the view of the actual object b) numerical model, generated by CFX Ansys

modified, which allowed to deal only with one half of it, assuming that in the other half the airflow is symmetrical. Such a procedure has made it possible to reduce the modelled space and, thus, to refine the discretization grid. Numerical model, after its modification, is to be seen in Fig. 2b. In the numerical cal-

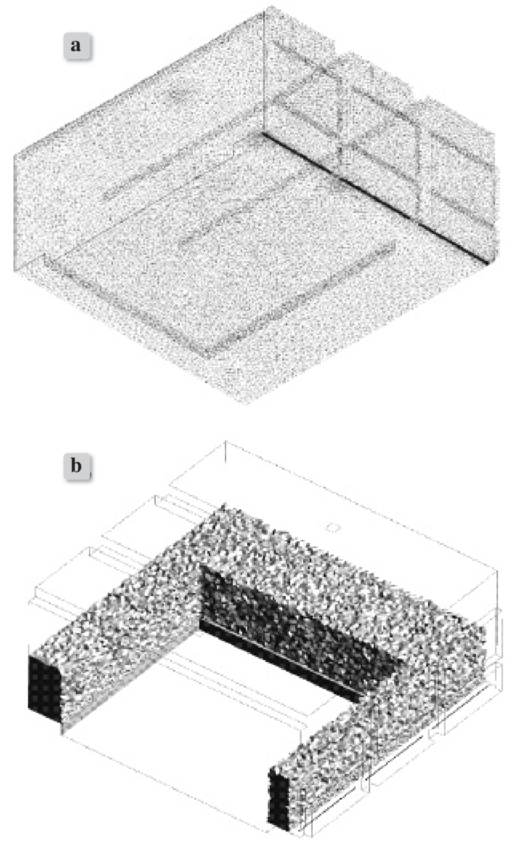

Figure 3.
Discretization grid in the numerical model of the roofed swimming-pool a) in the entire space b) in the occupied zone around the pool

Table 1.
Boundary conditions for simulation of the air distribution in the indoor swimming- pool in summer

Boundary condition	Parameter	Value	
Water in the pool	Temperature,°C	27.2°C	
	Humidity gain, kg/s	0.005666	
Wall	Heat flux, W/m^2	Ceiling	5.058
		Wall E and W: -	12.713
		Wall S:	-7.725
		Wall N: -	2.557
		Floor:	-11.392
		Window:	114.774
Inlet	Air volume rate, kg/s		0.732
	Intensity of the turbulence, %		5
	Air temperature, °C		32
	Specific humidity, kgH_2O/kg		0.0102
Outlet	Overpressure, Pa	0	

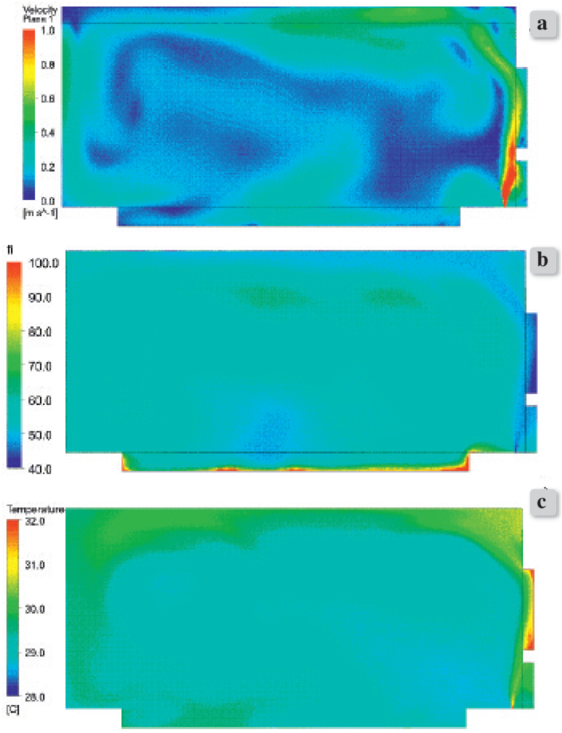

Figure 4.
Maps of the air parameters in the vertical plane of the hall in distance of 10m from the symmetry plane, generated directly by the post-processor of CFX Ansys code: a) average velocity, b) relative humidity, c) temperature

culations a six-equation BSL Reynolds Stress model of turbulence was used. Applied non-structural discretization grid, presented in Fig. 3, concerning the entire (a), and in more detail the occupied zone adjacent to the pool (b), consisted of 1976857 mostly tetrahedral elements.

The boundary conditions for the summer season, assumed in the calculations, have been presented in Table 1. To determine them, a heat and moisture balance sheet was made. The calculation comprised the heat flow penetrating each one of the walls, taking into account the gain of heat thanks to insolation, as well as heat transfer between the walls due to radiation, so that information concerning the mean radiation temperature of partitions could be obtained. The heat gains from the people were omitted. As we have to do with a swimming-pool in a school, it was assumed that the bathers were in the water all the time, so that the emitted heat was accumulated completely by the water.

The gains of heat and humidity from the surface of water were determined based on the standards [6]. The swimming-pool was modeled as a flat source of vapour with a constant emission of this substance all over the surface.

Based on the heat and moisture balance of the hall, the required supply air flow rate and its parameters were calculated. The air entered the hall through six slot inlets arranged in the floor under the windows, each of them consisting of two slots sized 2.6 m by 8.5mm each (Fig. 2b). They had been chosen following the catalogue of the producer [7], and modeled by means of the basic tools of the CFX code. In the roof there were six grills (sized 0.325 m by 0.325 m) through which the air was exhausted. Moreover, due to the already mentioned symmetry of the hall, the "symmetry" boundary condition was assumed in the symmetry plane (Fig. 2b). It enabled restriction of calculations to only one half of the hall.

5. POSSIBILITIES OF THE APPLICATION OF THE NUMERICAL CALCULATIONS DIRECT RESULTS FOR THE ASSESSMENT OF CONDITIONS IN A ROOFED SWIMMING-POOL

The results of numerical calculations of the air flow in a ventilated room may be presented immediately making use of the postprocessor of the CFX Ansys code. The first way of presenting the results are maps of the respective parameters, as shown as an example in Fig. 4 concerning the distribution of averaged velocity, temperature and relative humidity of the air in a selected plane of the swimming-pool. Colored maps provide much information about spatial distribution of the parameters and can show the shape of the jets or the dead zones in the hall. A disadvantage of this type of information is their subjectivism. The assessments and comparisons are only tentative and do not provide comparative numerical data.

A more accurate version of the colored map is a contour map of any single parameter, as shown on the example of the air averaged velocity distribution in the vertical plane of the room (Fig. 5a). In such a case concrete values are assigned to concrete regions, which permits to read-off the value of the parameter at this point. Another option of the map is possibility of presetting the value of layer boundaries. If, for instance, it is recommended to maintain the speed in the room below 0.2 m/sec, we can define the boundaries of the contour for this value. As a result we get the region in which this condition is satisfied. An example of such a map concerning the averaged velocity in the vertical plane is to be seen in Fig. 5b.

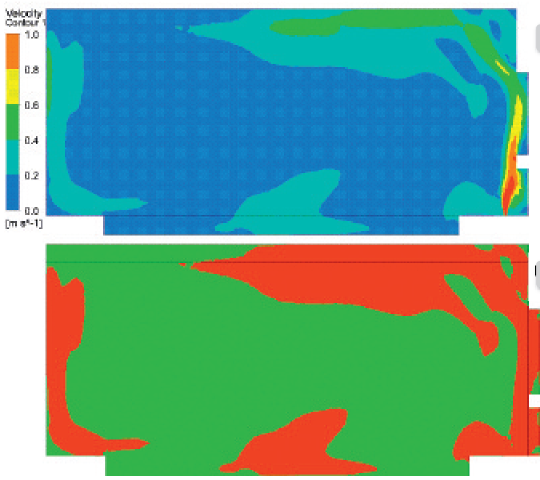

Figure 5.
Contour maps of the velocity in vertical plane in distance of 10m from the symmetry plane with the location of the contour lines: a) regular, b) made possible separation of the selected range of the parameter – the velocity higher (denoted red) and the velocity lower (denoted in green) than 0.2 m/s

By means of the postprocessor the data can also be obtained in the form of one parameter characterizing the whole room or only its part (lumped parameter), viz. the mean, maximum or minimum value in the entire modeled space or in some selected plane, e.g. in the occupied zone.

6. PROPOSED EXTENDED WAY OF ASSESSING CONDITIONS OF THE THERMAL COMFORT IN OCCUPIED ZONE

The maps obtained by means of the postprocessor, as well as the lumped parameters may be applied to assess thermal comfort and to compare the results of the application of different variants of air distribution in occupied zone.

These maps do not provide explicit information characterizing the given variant and permitting its numerical comparison with other instances of air flow. Lumped parameters are not always reliable quantities in such comparisons, both due to the way of their determination (e.g. taking into account the boundary layer values in calculation of mean value for entire plane) and to the fact that they do not characterize the spatial distribution of the parameters. Thus, for instance, in an indoor swimming-pool with a glass wall a considerable asymmetry in the distribution of temperature may occur during the winter season. Near the windows it may be too cold, whereas at the opposite wall, where the air is being supplied, it is too warm. But in spite of that, the mean temperature in the occupied zone proves incorrectly that the conditions in the occupied zone are satisfied. Therefore, an additional parameter is required, describing the spatial distribution of the parameter. Moreover, in the occupied zone simultaneously the effect of several air parameters on the perception of thermal comfort is observed, which cannot be taken into consideration when immediate results of numerical calculations are applied.

For this reason, a new way of assessing the condition of thermal comfort was suggested, supplementing the aforesaid drawbacks of the methods applied so far. This new method consists in determining the percentage of the area of the occupied zone cross-section at a given height where the criteria of thermal comfort are satisfied, using for this purpose CFD prediction.

In these calculations the postprocessor program CFX Ansys was applied, which permits to define and calculate the distributions of the values of the already mentioned parameters characterizing thermal comfort in the room, and to calculate the area in which these parameters are contained within the required limits. The application of this method was illustrated on the example of the investigated indoor swimming-pool, where in the occupied zone at the height of 0.1m, selected in compliance with the principles of assessing the conditions of the microclimate, various criteria had been taken into account.

The percentage of the area was determined, in which the temperature amounted to 28÷32°C (Fig. 6). Its share amounted to 100%, at a mean temperature of 29.1°C.

The determined percentage of the area, in which the relative humidity was contained within the range of 45 to 65% (Fig. 7) amounted to 92.0% at average relative humidity of 54.7%.

The percentage share of the area was checked in which the parameters of air, temperature and relative humidity, did not cause any excess of Lancaster-Castens-Ruge's sultriness curve at the indoor swimming-pool, as shown in Fig. 1. It amounted to 92.4% (Fig. 8).

According to the assessment in 61.6% of the considered area the air averaged velocity did not exceed the admissible value of 0.2 m/sec, at mean value o 0.19 m/s (Fig. 9). It ought to be stressed that based on the results of measurements the resultant value of veloc-

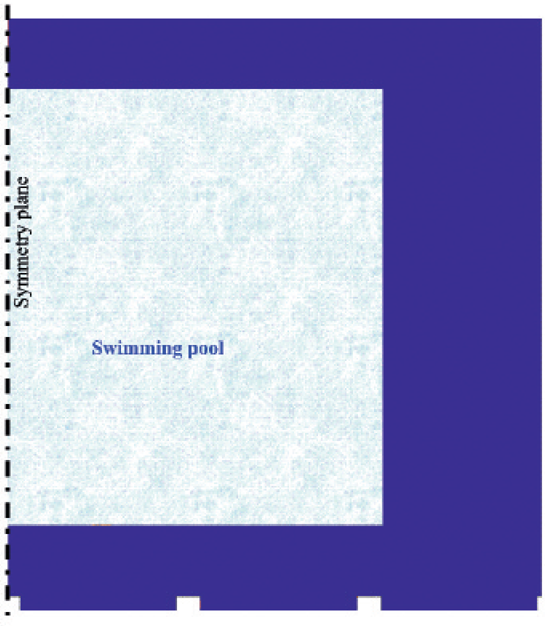

Figure 6.
Distribution of the air temperature in the occupied zone around the swimming-pool at a heigh of 0.1 m with the division into regions in which the condition of thermal comfort is satisfied (denoted in navy blue) or not satisfied (denoted in red)

Figure 7.
Distribution of the air relative humidity in the occupied zone around the swimming-pool at a heigh of 0.1 m with the division into regions in which the condition of thermal comfort is satisfied (denoted in navy blue) or not satisfied (denoted in red)

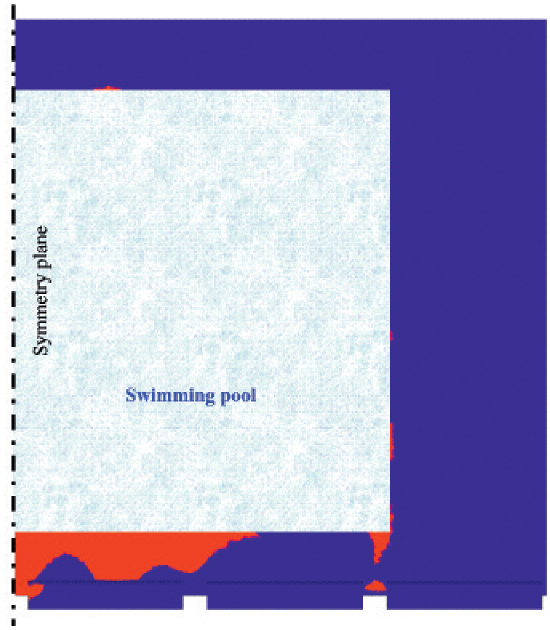

Figure 8.
Distribution of the areas in the occupied zone around the swimming-pool at height of 0.1 m with the division into regions in which the Lancaster-Castens-Ruge's sultriness curve is not exceeded (denoted in navy blue) or exceeded (denoted in red)

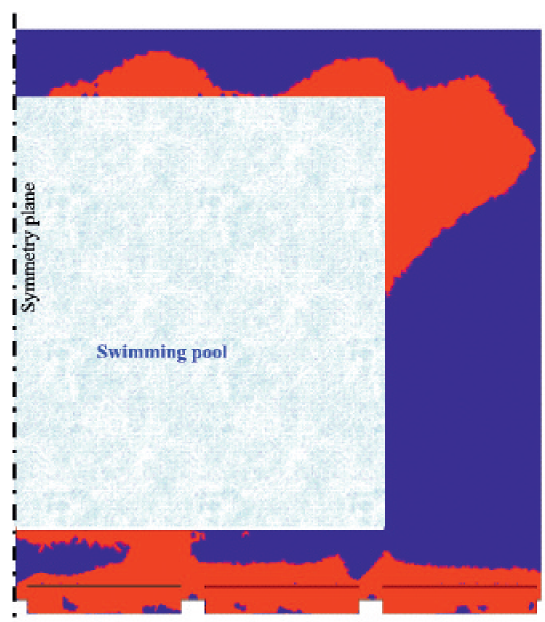

Figure 9.
Distribution of the air speed in the occupied zone around the swimming-pool at a heigh of 0.1 m with the division into regions in which the condition of thermal comfort is satisfied (denoted in navy blue) or not satisfied (denoted in red)

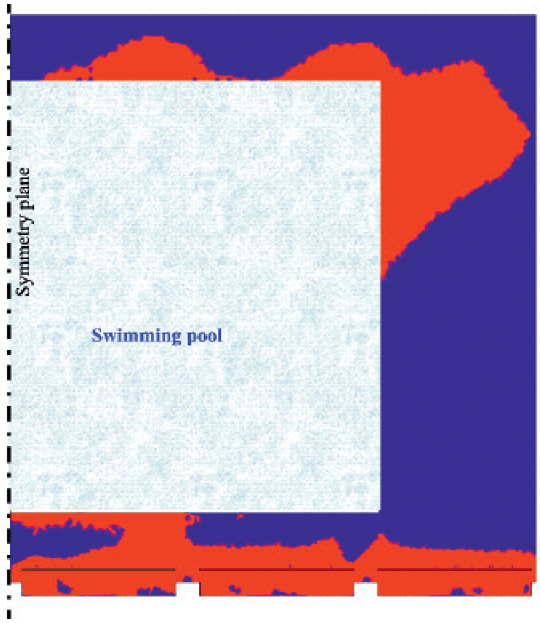

Figure 10.
Distribution of the PMV index in the occupied zone around the swimming-pool at a heigh of 0.1 m with the division into regions in which the condition of thermal comfort is satisfied (denoted in navy blue) or not satisfied (denoted in red)

Figure 12.
Distribution of the parameter Θ in the occupied zone around the swimming-pool at a height of 0.1 m with the division into regions in which the conditions of the ADPI index is satisfied (denoted in navy blue) or not satisfied (denoted in red)

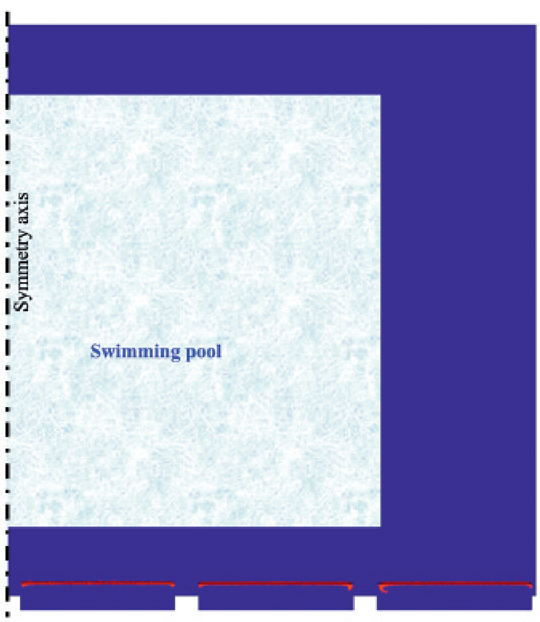

Figure 11.
Distribution of the DR index in the occupied zone around the swimming-pool at a hights of 0.1 m with the division into region in which the criterion of avoidance of local thermal discomfort is satisfied (denoted in navy blue) or not satisfied (denoted in red)

ity (speed) averaged in time was taken into account. Therefore, direct results of numerical calculations in the form of the resultant value of the velocity vector (velocity) averaged in time were corrected applying the method suggested by Popiołek [8].

Next, based on predicted values of temperature, speed and relative humidity, as well as on the mean radiant temperature and the assumed values of clothing insulation and metabolic rate concerning the people abiding at the swimming-pool, the distribution of the *PMV* index was calculated. The percentage of the share of the area was determined, in which it amounted to <-0.5, 0.5> (Fig. 10), i.e. 48.4%, and the mean value of this index concerning this plane was equal -0.23.

The next checked criterion was DR index. Based on numerically predicted values of temperature, speed and the intensity of turbulence (even that corrected in compliance with [8]), it was determined in which part of the area it did not exceed the recommended value of 20% of people realizing a local thermal discomfort (Fig.11), which amounted to 99.8% at average value of DR equal 4.80%.

The suggested way of assessment referred to and extended the method *ADPI*, applied until now based on the data obtained by measurements where only the temperature and speed of air were taken into account. The value of *ADPI*, calculated based on the predicted distribution of the parameter (Fig.12) and the value of the speed amounted in the investigated case to 48.6%.

7. CONCLUSIONS

The suggested method permits to assess numerically the results of applying such a system of distributing the ventilated air in a room, taking into account several factors affecting the conditions of thermal comfort in a room in the course of designing ventilation or air-conditioning. The larger the share of the area in which the required criterion is satisfied, the more favorable will be assessment of the given concept of the air distribution.

The assessment of thermal comfort concerning the selected concept of the air distribution inside the room, indicates that at the investigated height in the occupied zone in a considerable part of the area, requirements concerning temperature, relative humidity and speed of air were satisfied. Lancaster-Castens-Ruge's sultriness curve was exceeded only locally, and no draught was to be felt. In a considerable part of this area, however, the conditions of thermal comfort could not be achieved, so that the values of PMV index would be realized, and thus also the values of PPD index, required in case of this category of rooms.

Such an assessment is possible at various heights above the floor in the occupied area. It may also be carried out over the entire volume of this zone. It allows to state that the conditions of thermal comfort need to be improved by applying another concept of air distribution of in the investigated indoor swimming-pool. The choice of an optimal concept enables also the application of the suggested method, thanks to which the effect of different variants of ventilation may be compared with each other. The results of such analyses are the subject matter of separate paper.

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