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Thermal comfort study of naturally ventilated office

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Abstract. It is well known that people spend about 90% of their lifetime in buildings where the indoor environment strongly influences their health and productivity. Therefore it is crucial to maintain proper internal conditions, and thus ensure comfort environment for building users. Due to the nature and complexity the thermal comfort is difficult to describe with physical parameters. However there is a number of available methods to assess the indoor conditions and define the comfort level - from simplified methods based on the measurement of basic parameters to complex approach – with the use of computational fluid dynamics engineering tools. The paper presents the outcome of the thermal comfort study for a naturally ventilated office located in Wroclaw (Poland). The chosen physical parameters has been registered in long- and short-term perspective, and later used for defining the boundary conditions and CFD model validation.

1 Introduction

People spend most of their time indoors. The building is a shelter from external conditions, so the interior has to be safe and comfortable for its users. The building environment strongly influences not only human comfort, but also the life, activity, health and productivity. Therefore the main concern of the engineers and researchers is to identify crucial factors and parameters influencing thermal comfort and maintain them on expected level. The combination of these physical and individual variables defines levels of thermal comfort and thus the user's satisfaction from the thermal environment. There is a certain number of methods to estimate the thermal comfort in rooms – from simplified, based on the variability of one parameter to complex approaches – based on the relationship between environmental and personal factors or implementation of numerical tools. These methods are still evaluating and are under improvement as they have limitations depending on outdoor conditions, building types, specific requirements of the users or the installations the building is equipped.

The indices and methods for estimating thermal comfort are evaluating from the 1930s [1]. Today the most common methods are based on Fanger's theory and operative temperature approach and are described in the European Standards 7730 and 15251 [2, 3]

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respectively. The simple method based on relationship between the air temperature and relative humidity but under constant clothing insulation value (clo) of 0,6 and sedentary activity was developed by Rholes [4] His extended model dedicated for wider range of clo was described by Burati et all. in [5]. The adaptive predicted mean vote (aPMV), Human Thermal Model (HTM), adaptive comfort algorithm (ACA) in comparison with classic comfort approach represented by Fanger's theory are described in paper [6] as methods more flexible than classic adaptive approach. The example of the application of most complex approach in comfort study based on CFD modelling is described in [7]. The literature presents also examples of comfort study for mechanically ventilated enclosures [8, 9, 10] as well as naturally ventilated buildings [11–13].

The paper focuses on estimating comfort conditions in naturally ventilated office located in Wroclaw (Poland). The applied method is based on an approach described in standard EN 15251 [3]. It assumes that in naturally ventilated buildings working in free-running mode human body easier adapts to the surrounding due to his/her thermoregulation system. It is applicable for free-running buildings as well as periodically heated, cooled and running under a mixing mode, and is based on a theoretical value – an operative temperature. This method combines two parameters that need to be measured, namely indoor air temperature and mean radiant temperature. The literature [14] indicates that in well-insulated buildings, where the influence of exterior is small, the difference between air, mean radiant and thus operative temperature is negligible. To check this theory the relationship between these parameters is investigated and the statistical methods are applied. The investigated office was also subjected to a long-term assessment and CFD modelling. Therefore the last part of the article presents the outcome of these analysis.

The European Standards [2, 3] define also other methods for steady- and not-steady-state conditions based on temperature drifts, temperature steps, cycling temperatures or temperature ramps. However these are not under the interest of this paper.

2 Comfort study

2.1 Investigated room

The study was conducted in the naturally ventilated office room located on the first floor of the two-storey building. The main geometry data: room area equals 21,3m^2, room clear height is 3m, clear length of the external wall is 5,1m, two windows of 112x150cm. The room geometry is presented on the Fig. 1. The external wall and windows are directed towards south-west. The comfort conditions during heating season in the office are provided by classic radiator-based water system. In summer office works in a free-running mode. The European Standards [2, 3] defines the range of comfort operative temperatures depending on the class of the building. The investigated room can be classified as category II (B) – dedicated for renovated buildings or cat. III (C) – for existing buildings. In winter time the operative temperature range for cat. II (B) is defined as 20–24°C for cat. III (C) is defined as 19–25°C. The limit values for summertime are described by proper equations described in [3].

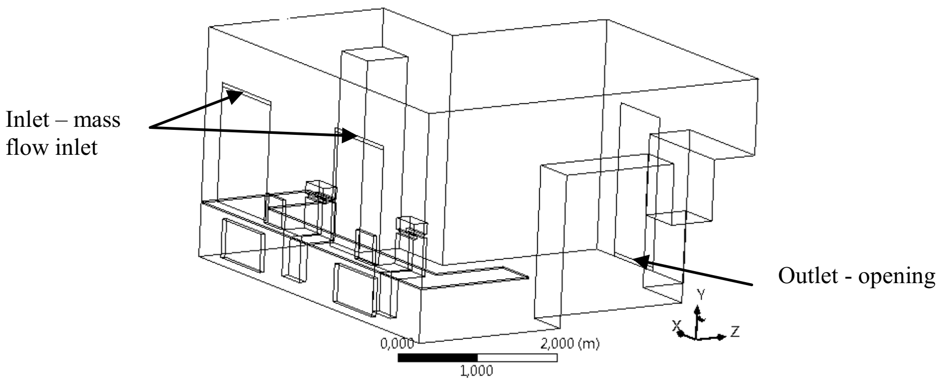

Fig. 1. Geometry of the investigated office with the description of main boundary conditions.

2.2 Indoor air temperature measurements

Measurement of air temperature in the room was performed continuously during the period from February to December 2014 in the 10-minute interval. The following data loggers have been used: Volcraft DL-141 TH with the accuracy of ±1°C for the temperature range from -10°C to +40°C and Rotronic CL11 with the accuracy of ±0,3°C for the temperature range from 0°C to +50°C. The variation of recorded parameter is presented on the Fig. 2. The surface temperatures were measured by the set of thermocouples connected to the logger.

Fig. 2. The internal temperature variation during measurement period: 26.02.2014 to 19.12.2014.

The recording period started at 11:05 a.m. on 26th of February 2014. The last measurement took place at 14:15 p.m. on 19th of December 2014.

The highest temporary internal temperature of 32,7°C was measured during the night time on 21st of July when the office daily-average was 32,14°C. The lowest temporary internal temperature was recorded during morning hours (between 6 and 8 a.m.) on Monday the 8th of December and reached 18,1°C. The highest temperature at this day occurred between 6 and 7 p.m. when the mean external temperature was +1°C and reached 20,7°C.

2.3 Operative temperature

The air temperature and its variation are the main environmental parameters in comfort level estimations, however the most common simple indicator is an operative temperature.

It is a pure theoretical value, thus it cannot be obtained directly due to an empirical study. The operative temperature can be calculated from [14]:

$$T_o = H \cdot T_a + (1-H) \cdot T_r \quad (1)$$

where T_a is air temperature; T_r is mean radiant temperature; H is a value described by the relationship between convective heat transfer coefficient and linear radiation transfer coefficient. The H parameter is difficult to estimate and differs between researchers, therefore CIBSE (UK Charter Institution of Building Services Engineers) proposed to correlate the T_{op} with the air velocity [14]. For natural convection it can be assumed to be 0,1m/s thus the simplified equation describing operative temperature can be written as [14]:

$$T_o = 0{,}5T_a + 0{,}5T_r \quad (2)$$

To estimate the value of operative temperature and its variation for investigated office the inner surface temperatures of surrounding surfaces was recorded over the period of time: from 26th of September to 4th of December. The mean values of measured parameters and calculation outcomes are presented on the Fig. 3. The gap in data collection from 1st to 13th of November was caused by fluctuating problems with electrical network in the building and thus recording equipment.

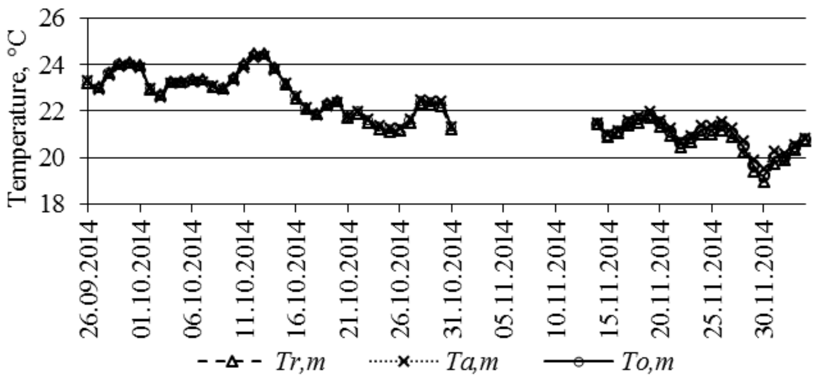

Fig. 3. The variation of mean values of radiant temperature ($T_{r,m}$), room air temperature ($T_{a,m}$) and operative temperature ($T_{o,m}$).

Data presented on the Fig. 3 clearly states that during the considered period, the discrepancies between mean indoor air and radiation temperature is negligible, and thus the variation of the operative temperature is close correlated with the room temperature.

2.4 Statistical relationship between air and radiant temperature

The statistical analysis is an important part of each scientific research. Therefore this paragraph presents the results of the statistical analysis of the relationship between indoor air temperature and the temperatures of surrounding surfaces, and their influence on the office air temperature. Persons correlation coefficient (r) defines strength of relationship between independent variables and p-value defines statistical significance of the relation for particular set of data points. The value of the coefficient can vary between -1 and 1, and thus the correlation is assumed to be strong if $|r|$ is bigger than 0,7 or medium to week if $|r|$ is in the range of <0; 0,7>.

The calculated Pearson correlation coefficients for the relationship between the indoor temperature and the temperature of inner surfaces of external wall, windows and flat roof were calculated and amount respectively 0.973; 0.855 and 0.989 what proves strong relation between analyzed data.

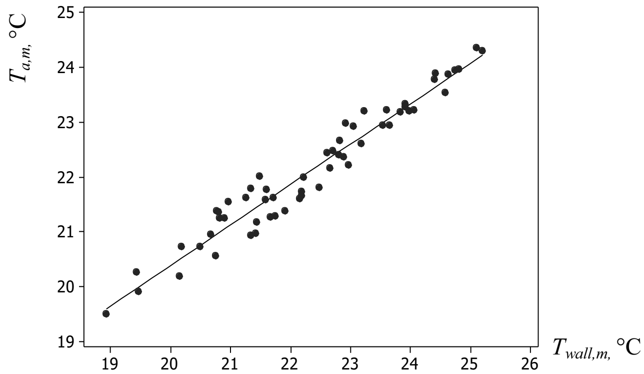

Fig. 4. Function 1 – describes the relationship between mean (daily-average) indoor temperature $T_{a,m}$ and mean temperature of the inner surface of external wall $T_{wall,m}$.

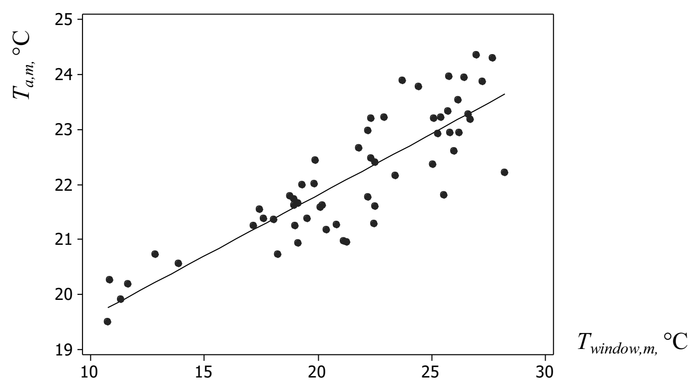

Fig. 5. Function 2 – describes the relationship between mean (daily-average) indoor temperature $T_{a,m}$ and mean temperature of the inner surface of windows $T_{window,m}$.

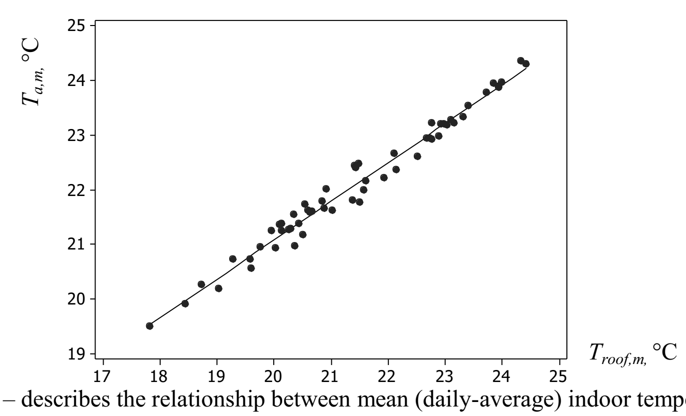

Fig. 6. Function 3 – describes the relationship between mean (daily-average) indoor temperature $T_{a,m}$ and mean temperature of the inner surface of flat roof $T_{roof,m}$.

To define functions describing the mathematical model of the relationship between air temperature and the temperatures of surrounding surfaces (and thus the room radiant temperature), the regression analysis has been applied.

The outcome of the analysis in graphic forms are presented on the Fig. 4., Fig. 5., Fig. 6. The mathematical equations describing these relationships are presented in Table 1. The residuals analysis which is out of scope for this paper.

To check the statistical significance of the correlation between the analyzed parameters, the significance level of 0,05 was assumed as for engineering applications. In all three cases the calculated P-value was lower than 0,05. Therefore, the null hypothesis H_0 that the data are independent is rejected and the alternative hypothesis H_a of a statistical significance is adopted. Present statistical significance (P-value) and strong variables correlations (*r*) are also confirmed by high value of determination coefficient R^2 for each function (Table 1), what is typically called “practical” significance and can be read as portion of real data variation explained or determined by the particular math model.

Table 1. The determination coefficients R^2 for the functions describing the relationship between the daily-average indoor temperature and the temperatures of internal surfaces of the building envelope.

Function no.	**Mathematical model**	**Determination coefficient R^2**
Function 1	y=5.612+0.7386x	94.7%
Function 2	y=17.35+0.2228x	73.0%
Function 3	y=6.859+0.7108x	97.7%

Presented in Table 1 models describe very well the relationship between discussed parameters therefore at this stage of the investigation there is no need for expanding the models for bigger number of freedom of the subsequent points or introducing new variables increasing the models complexity.

The proposed equations can be applied at the later stage of the research as a boundary conditions when considering CFD simulations of the office under dynamic state. However it is not the scope of this paper.

2.5 Long–term comfort assessment

The other approach of estimating comfort conditions assumes long-term measurements as described in [3]. The method classifies the enclosure to one of four categories of indoor conditions and is based on the daily average room temperature during the heating period.

Table 2. The percentage of time for a given temperature range (defined for a particular class of the building) in monthly cycle (on 24-hours basis).

Building category/ Month	**I**	**II**	**III**	**IV**
March	19.5%	45.4%	34.1%	1.0%
April	91.5%	6.8%	1.7%	0.0%
October	63.5%	29.4%	6.6%	0.5%
November	67.4%	23.9%	8.7%	0.0%
December (19 days)	19.0%	49.7%	21.7%	9.6%

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Following [3] the room initially was classified as category III (with lower standards of comfort, as described in section 2.1), but the analysis of the temperature during office "working hours" indicated that the room can be classified as cat. II (with the percentage of people dissatisfied lower than 10% [2]).

Additional analysis of the percentage of time in a given month on a 24-hours basis when the office meets the class requirements has been performed. The time of occurrence of the temperature range corresponding to different classes of buildings is presented in Table 2.

2.6 CFD simulations

In the final stage of the investigation, the office was simulated in ANSYS (CFD tool) under steady – state conditions. The created geometry (Fig. 1) was divided on a certain number of control volumes. The defined boundary conditions are presented in Fig. 1. The other elements are defined as surfaces with constant temperature (taken from the measurements) or as adiabatic walls. For the simulation SST k-ω turbulence model was applied [8, 10]. The simulation outcomes are presented on Fig. 7 and Fig. 8.

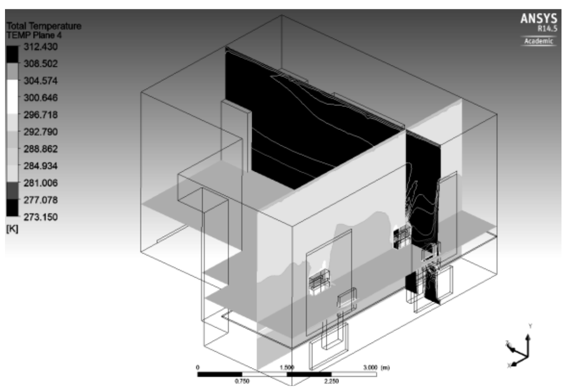

Fig. 7. The temperature distribution profile in a three control planes.

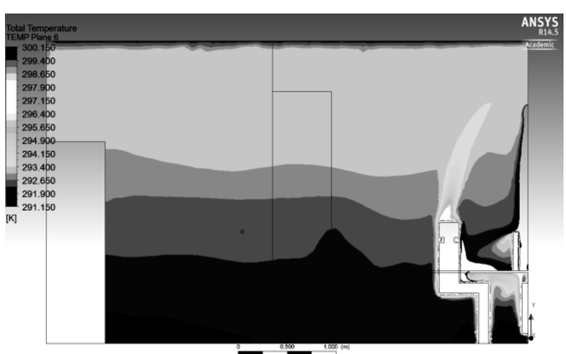

Fig. 8. The temperature distribution profile in a vertical plane. The temperature range: 18ºC to 27ºC.

The resulting maps of temperature in simulated office are in line with expectations. Measured room temperature for given boundary conditions was 20,5ºC. According to the model, this level of temperature is achieved at about 1,7 m, which well corresponds with the sensor position and its readings within the tested room.

3. Conclusion

The paper presented chosen methods of assessing comfort conditions that can be applied for naturally ventilated rooms. The measurements of indoor temperature and surrounding surfaces were undertaken to calculate operative temperature, to perform long-term estimation of comfort, to define boundary conditions of the CFD office model and to compare with the simulation outcomes. The statistical analysis, as an important element of the scientific research, was applied. It was based on the regression method to establish and validate the relationship between measured parameters.

The paper indicated that there is a number of well described in the literature methods of assessing indoor comfort conditions. From the simple and common to the advanced and complex approaches, in short and long perspective. Each method has its own limitations and applicability. However, as thermal comfort is an important aspect in terms of building operation, satisfaction and productivity of building users, therefore the comfort investigation, even by application of simple methods, should be an important element of engineering practice.

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