Use of CFD modelling for analysing air parameters in auditorium halls

Robert Cichowicz[1,2,*]

[1]Lodz University of Technology, Faculty of Architecture, Civil and Environmental Engineering, Al. Politechniki 6, 90-924 Łódź, Poland
[2]Venture Industries Sp. z o. o., Mokra 27, 05-092 Łomianki – Kiełpin, Warszawa, Poland

Abstract. Modelling with the use of numerical methods is currently the most popular method of solving scientific as well as engineering problems. Thanks to the use of computer methods it is possible for example to comprehensively describe the conditions in a given room and to determine thermal comfort, which is a complex issue including subjective sensations of the persons in a given room. The article presents the results of measurements and numerical computing that enabled carrying out the assessment of environment parameters, taking into consideration microclimate, temperature comfort, speeds in the zone of human presence and dustiness in auditory halls. For this purpose measurements of temperature, relative humidity and dustiness were made with the use of a digital microclimate meter and a laser dust particles counter. Thanks to the above by using the application DesignBuilder numerical computing was performed and the obtained results enabled determining PMV comfort indicator in selected rooms.

1 Introduction

The assessment of the interior environment should be carried out in relation to numerous physical-chemical factors, because their changes can influence the quality of the interior air [1]. The above is the consequence of the fact that in rooms at the same time there can stay different groups of people, and accordingly there can be noted a variable level of air pollution and different amount of heat and humidity [2–3].

One of the most important parameters of air quality is CO_2 concentration in the air, because it influences the effectiveness of work of people in a given room (concentration above 1000 ppm causes the feeling of discomfort and drowsiness [4–5]). Whereas there exists yet another equally significant factor having a negative influence on wellbeing. The factor is dustiness in a room, which even in a very low concentration can be a threat for health [6–7]. Due to this reason each system of mechanical ventilation installed in a building occupied by people should be designed to provide for the necessity to remove the appearing pollution and gains of heat and humidity [8]. It should also be remembered that when carrying out renovations of ventilation systems and controlling the internal

* Corresponding author: robert.cichowicz@p.lodz.pl

environment it is important to concentrate also on thermal comfort of the persons staying in a given room [9].

When analysing the sensation of comfort while staying in a room one of the basic needs of human organism should be taken into account, which is maintaining a stable body temperature. In order to fulfil this condition it is necessary to maintain the balance in a number of parameters. The elements of heat exchange between a person and the environment are the following: energy expenditure, air temperature, average temperature of radiation, partial pressure of vapour, air speed and resistance for heat conductivity through clothing (the equation describing the phenomena taking place between a human organism and the environment has been determined by Fanger). In order to determine the distribution of comfort indicator it is necessary to determine the value of metabolism of the people staying in the room and the insulation properties of their clothing. A person's metabolism is defined as the energy returned to the environment obtained by means of chemical processing of eaten food (its unit is 1 met, which means 58.2 W/m^2 of the returned energy and characterises a person at rest) [10].

The assurance of thermal comfort means the necessity to determine whether specific parameters have been fulfilled. The parameters include temperature proper for a given room, relative humidity and, in case of mechanical ventilation being installed in the room, appropriate speeds of air flow in the human presence zone (the data is usually needed to carry out various types of computer analyses) [6, 11].

Also other parameters that significantly influence the conditions sensed by the persons in a room, such as temperature of partitions, type of heating system and distribution of temperatures in a room, have to be specified [11].

All these parameters generate a great amount of data, difficult to analyse each separately in a transparent and fast way. Therefore a PMV indicator is used. The indicator provides for 6 variable parameters, such as: relative humidity, temperature, air speed, average temperature of radiation, the level of activity of persons in the room and insulation properties of clothing. The range of the indicator includes values from -3 (sensation of being cold) to +3 (sensation of being hot). Whereas the level of comfort in a given zone of the room is assured when the indicator remains within the range from -0.5 to +0.5 [6, 12]. In order to correctly interpret the obtained results cross-sections of the room with distribution of the indicator at the height of 1.1. above the floor has to be analysed in case of auditory halls, because this height is analogous to the location of heads of people in a seated position.

Determining proper conditions for a given room demands defining its purpose. An auditory hall is a place that can accommodate as many as a few dozen or even a few hundred people. In rooms of such dimensions it is critical to maintain comfort in the zone of human presence. It is a common case that the temperature or air speed outside of this zone can be far from accepted standards. The reason for that can be the lack of possibility to supply the room with an appropriate amount of air and at the same time to maintain in the whole cubature of the room of the air speeds that are not sensed by the rooms' users (the problems usually occur in high rooms) [3].

In accordance with the standard ISO 7730:2005 [13] for rooms having the properties of auditory halls the air temperature in the heating season should be maintained within the range from 20°C to 24°C, and in the summer season between 23 and 26°C. Requirements for relative humidity are 40% to 60% during winter and 30–60% in summer. Yet it has to be remembered that when analysing the comfort of seated persons, the speed of air should be controlled in the zone of human presence so as not to exceed 0.19 m/s in summer and 0.16 m/s in winter [13].

2 Numerical modelling

Computational Fluid Dynamics (CFD) enables analysing fluids flow together with heat exchange between them. CFD is more and more popular in modelling the phenomena taking place in interiors. Thanks to the use of this method already at the stage of architectural and building structure design it is possible to analyse the best solution for the whole building as well as for its ventilation or the air-conditioning system, and thus it is possible to reduce the costs of prospective possible failures or modernisation [3].

CFD modelling enables providing for proper ventilation openings, speeds of the intake air and the range of the streams of an assumed speed. It is also possible to optimise a given design from the perspective of assuring the best possible comfort conditions in a room, taking into account convection movements caused by the presence of people in the analysed space [14].

The existing computer software enables modelling by discretizing variable equations into algebraic equations, which is associated with assuming certain approximations, i.e. limiting the model with the use of one of the following methods: differences, capacity or finite elements. It is also always important to introduce specific boundary conditions into a mathematical model [15]. Calculations in computer applications are usually performed with the use of a three-dimensional net, which describes the analysed space with a selected accuracy [14, 16].

In order to start the work on a selected building or a room it is necessary to specify its shape in the application. This stage is very important and time consuming. The analyses presented in the article have been performed in DesignBuilder, an application characterised by intuitive use and by adjustment to modelling of any type of building. The application enables analysing models form the perspective energetic effectiveness, building costs and optimisation of interior systems. DesignBuilder also has a module for performing CFD calculations for a building as well as for its surroundings [17]. Also by introducing required input parameters it is possible to carry out numerical computing, thanks to which distribution of temperature in a room and range of air stream of a characteristic speed are obtained [3, 14, 18].

3 Methodology of measurements

Experimental research was carried out in auditory halls. The first of the halls, marked as A has the total area of 118.68 m^2 (the highest point in the hall is located at the height of 6.20 m) and is designed for 110 persons. The hall is equipped with a system of mechanical intake-exhaust ventilation with a constant capacity of 5550 m^3/h. Another hall, marked B, has no windows, and is the largest of the analysed rooms (its area is 199.21 m^2, and the maximum height is 5.90 m). The last of the analysed halls, marked as C, is a mirror reflection of the auditory hall A.

In all the three auditory halls a microclimate research was carried on, and thus information necessary to perform the CFD analysis in DesignBuilder application was obtained. A digital meter of microclimate BABUC/A was applied. With the use of this meter the air parameters, among others the temperature of the surroundings and relative humidity were determined. Also the temperature of surfaces of partitions in the room was measured. Additionally such parameters as metabolism, the average relative humidity and insulation properties of clothing were determined (obtained decomposition indicator PMV). The measurements were supplemented with the research on dustiness of the outdoor air. They were performed with the use of laser particle counter Icleen PCM. In the halls measurement points were determined (Fig. 1). In these points two series of measurements were performed (in the halls A and C they were made with windows closed and open), and each measurement had a duration of 10 minutes ($\sum = 2 \times 3 \times 10$ minutes).

4 Results of measurement and numerical calculations

The following parameters were measured for all the auditory halls: the temperature of the surface of the external or inner walls, if applicable – windows temperature, the temperature of the supplied air and the temperature of radiators. This information was introduced into the computer application as boundary conditions for further analyses (table 1).

Table 1. Parameters necessary for numerical analyses performing (boundary conditions).

Temperature of external walls	19.0°C
Windows temperature	17.0°C
Temperature of inner walls	21.0°C
Temperature of supplied air	21.5°C
Temperature of the surface of central heating elements	30.0°C

In order to perform calculations and simulations of air flows in particular auditory halls the values of inflowing and removed stream were provided in post-completion documentation of the mechanical intake-exhaust ventilation system.

In the auditory hall A the model was assumed in which the room was filled with students in order to present the most unfavourable conditions. The effect of such an assumption is Fig. 1, which presents distribution of temperatures with the vectors of air speed in the analysed room, with special stress put on the human presence zone.

When analysing the presented results of calculations (Fig. 1) a great influence of persons in the room on distribution of temperature and air speed in the room can be noted. Considerable heat gains from people cause additional convection movements, and the niche, visible to the right on the cross-section, has a negative influence on the comfort of being in the room due to warm air that gathers there. A solution to this problem could be accepting the concept proposed by Koper P. and Lipska B. M. [3], who suggest that the best way to divide the air is by application of an upper nozzle air supply from the back of the room together with a low exhaust along the stairs. Such an arrangement could also improve distribution of temperature in a room, because the application of ceiling anemostates would heighten temperature in the human presence zone.

 DOI: 10.1051/e3sconf/20172200030

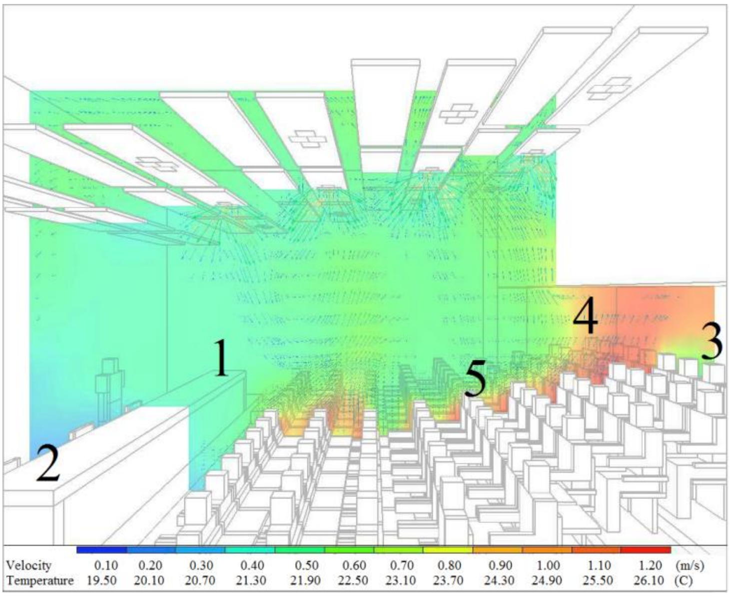

Fig. 1. Distribution of temperature and the vectors of speed on the cross-section of the auditory hall.

Fig. 2 and 3 present distribution of PMV indicator, which was shown from two different levels, in order to assess thermal comfort of the persons staying in the zone of the room designed for human presence. The distribution was achieved by introducing the metabolism of persons staying in the room at the level of 1.2 met [13], insulation properties of clothing as 1 clo and the average relative humidity calculated on the basis of measurements as 34%.

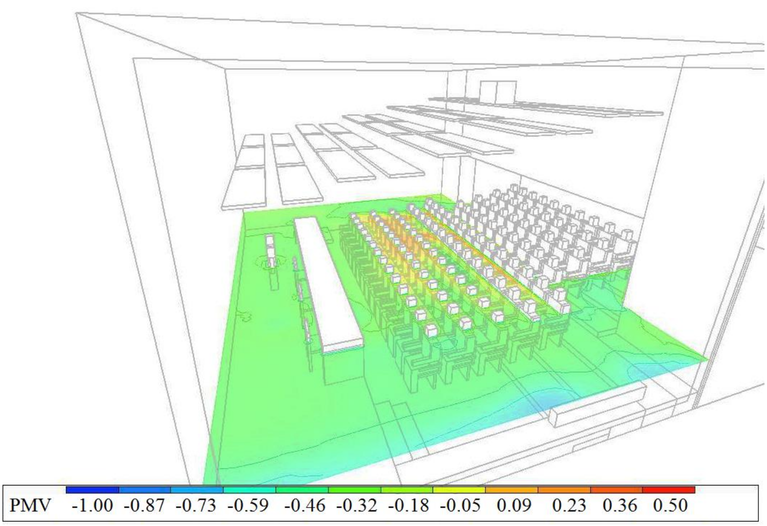

Fig. 2. Distribution of PMV indicator at the height of 1.1 m.

In the zone of human presence the obtained values of PMV indicator are included within the recommended range of values from -0.5 to 0.5. Such a distribution of indicator suggests fulfilment of all conditions of comfort. Whereas low temperature of windows' surface causes the situation in which in their proximity the indicator drops to the value below -0.5. Yet due to lack of sitting places in this area, this situation has no direct influence on the sensation of thermal comfort in the room.

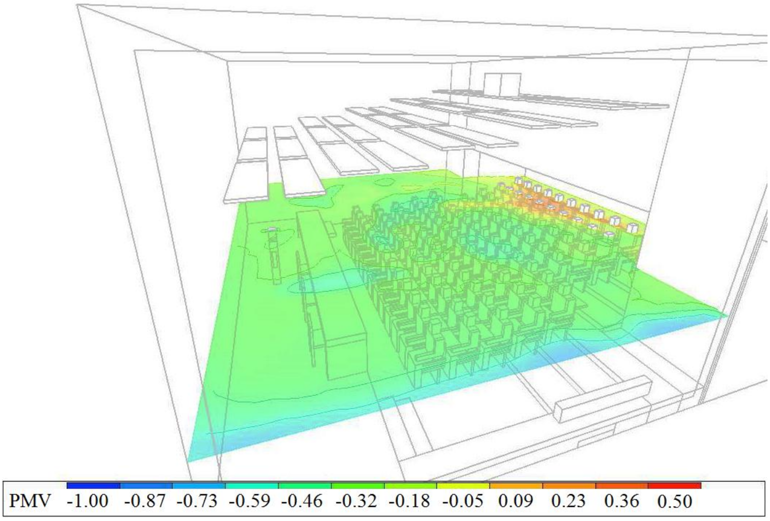

Fig. 3. Distribution of PMV indicator at the height of 2.1 m.

Fig. 4 presents the change of value of dustiness referred to the period of performing the measurements in all the three auditory halls.

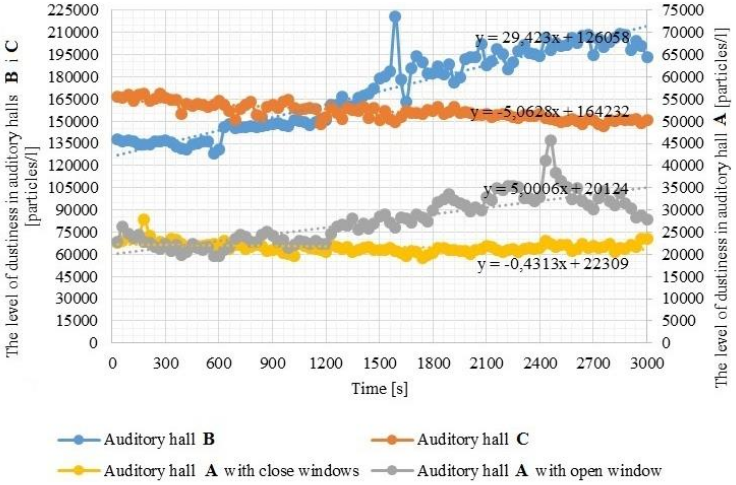

Fig. 4. The level of dustiness in time in auditory halls.

During the measurements in auditory hall B the ventilation system was switched on, and measurements in each following point indicated the increase of dustiness values (blue line on Fig. 4). This visible relation between the mechanical ventilation system work and the increased level of dustiness has also been observed by other scientists, According to Parker J. L., Larson R. R., Eskelson E., Wood E. M. and Veranth J. M. [19] a mechanical ventilation system is the main factor causing dustiness in rooms. While on the basis of measurements made in the auditory hall C, a constant level of dustiness was observed when the ventilation system was switched off (orange line in Fig. 4). This relation was confirmed by the results of measurements performed in hall A (yellow line in Fig. 4) because with the ventilation system switched off the level of particles concentration in the whole room remained between 21000 and 22000 particles/l, while opening of the windows caused the

 DOI: 10.1051/e3sconf/20172200030

increase of dustiness in time (grey line in Fig. 4). It can also be seen while analysing the levels of dustiness depending on the location of a given measurement point (Fig. 5).

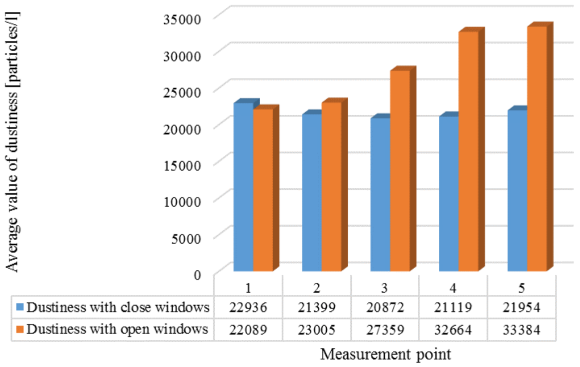

Fig. 5. The average value of dustiness in measurement points in room A with closed and open windows.

The results of measurements presented in Fig. 6 show a constant temperature of around 20°C. It can be noticed that opening of the windows caused a drop of relative humidity from 31.5% to 27.5%. The average value of dustiness from all measurements is 27700 particles/l. The lowest dustiness was measured in point 1, and it was lower from the average dustiness in the hall by 20.3%. While in the 5th measurement point the dustiness was the highest, and it exceeded the average dustiness by 20.5%.

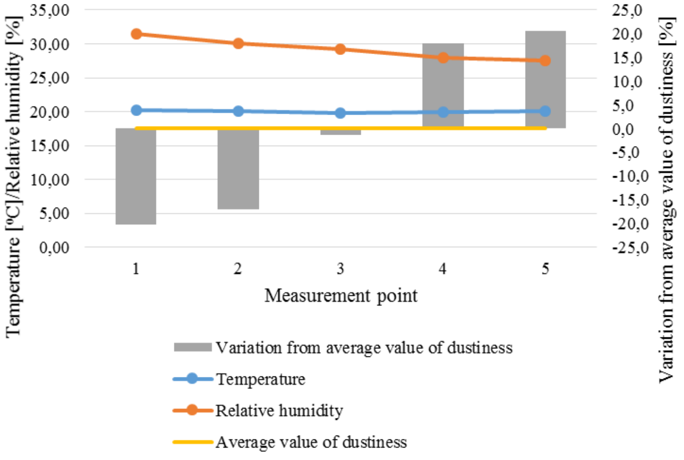

Fig. 6. Average dustiness, temperature and relative humidity in measurement points in room A.

5 Summary

Numerical calculations performed with the use of CFD enabled obtaining precise distributions of temperature and air speed in selected auditory halls. This in turn enabled determining the PMV indicator for all rooms, thanks to which it was possible to assess the conditions of thermal comfort in the zone of human presence. By analysing the obtained results it was found out that in all the rooms conditions for parameters of the environment temperature and air speed are compliant with the standard ISO 7730:2005 [13], and the PMV indicator ranges within the recommended -0.5 to 0.5 (of course with the assumed values for metabolism, insulation properties of clothing and relative humidity).

 DOI: 10.1051/e3sconf/20172200030

On the basis of measurements of air dustiness the influence of mechanical ventilation system on the increase of dustiness in a given room was stated. The dustiness in the analysed auditory halls increased significantly during ventilation through airing. Whereas when analysing the dependence of the number of dust particles in the function of relative humidity in a room, a drop of dustiness together with the increase of relative humidity was observed.

Acknowledgements

The author thank Mr. Jakub Florek MSc. for its contribution to the measurement of air samples and for his assistance technical support in graphic design work.

References

1. M. Kavgic, D. Mumovic, Z. Stevanovic, A. Young, Energy and Buildings **40**, 1334–1343 (2008)
2. A. Leavey, Y. Fu, Building and Environment **85**, 287–297 (2015)
3. P. Koper, B.M. Lipska, Ciepłownictwo, Ogrzewnictwo, Wentylacja **41**, 7–8 (2010)
4. R. Cichowicz, H. Sabiniak, G. Wielgosiński, Ecol. Chem. Eng. S. **22**, 1, 61–71 (2015)
5. I. Salma, Atmospheric Environment **64**, 219–228 (2013)
6. ISIAQ-CIB Task Group TG 42: Performance criteria of buildings for health and comfort, CIB **292 (**2004)
7. Z.B. Klaić, Geofizika **32** (2015)
8. R. Cichowicz, G. Wielgosiński, A. Targaszewska, Ecol. Chem. Eng. S. **23**, 1, 49–60 (2016)
9. Y. Fu, M. Sha, Proceedings – International Conference on Distributed Computing Systems **8**, 73–82 (2014)
10. S. Gilani, M. Khan, W. Pao, Energy Procedia **75**, 1373–1379 (2015)
11. P.O. Fanger, *Thermal comfort* (Arkady, Warszawa, 1974)
12. A. Garnier, J. Eynard, M. Caussanel, S. Grieu, Journal of Process Control **24**, 6, 750–762 (2014)
13. ISO 7730:2005: Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. (2005), with amendments
14. B. Lipska, Ciepłownictwo, Ogrzewnictwo, Wentylacja, **10** (1999)
15. J.K. Calautit, B.R. Hughes, Building and Environment **80**, 71–83 (2014)
16. T. Mikeska, J. Fan, Energy and Buildings **107**, 59–67 (2015)
17. http://www.designbuilder.co.uk/
18. B. Lipska, A. Palmowska, P. Ciuman, P. Koper, Instal, **3** (2015)
19. J.L. Parker, R.R. Larson, E. Eskelson, E.M. Wood, J.M. Veranth, Indoor Air **18**, 5, 386–393 (2008)