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Analysis of indoor temperature in the workshop building during the summer: a pilot study

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Abstract. The aim of this paper is the presentation of measurements' results and the calculation method for analysis and evaluation of climate conditions as well for using of natural illuminance in two large simple buildings during summer which could be used to calculate power demand for the air cooling to reduce the indoor temperature caused by solar radiation. In this research, we carried out experiments of measuring the indoor temperature at level of working place which is 1.1 m, in two similar large workshops with floor area 260 m^2 and height 6.5 m, during several hot summer days. The indoor conditions were strongly influenced by the solar radiation as the buildings have large wall and roof windows. The indoor air temperatures in the first building achieved 39.5 °C, which caused the heat stress for workers. The indoor air temperatures in the second building achieved only 29.5 °C. The calculated power demand for the air cooling to reduce the indoor temperature to 25 °C is 25.6 kW in the first building, the cooling power for second building is 14.9 kW. We investigated measured construction of the workshop and we set up the formula in order to calculate thermal balance. The measurement results and calculated results in two buildings are compared and summarized in the tables and in the graphs for analysis. As a general conclusion, it must be said that solar radiation has a big influence on the air temperature and methods of passive air-conditioning should be more applied also on the production buildings in industry, agriculture and other branches of civil engineering to release heat increasing air temperature inside the building.

Key words: air conditioning, inside temperature, solar radiation, thermal balance.

INTRODUCTION

Indoor temperature is part of the indoor environmental quality component that is influenced by the climatic condition and construction of place (Randall, 2006). A successful indoor environment greatly depends on an understanding of the environmental factors, including building design and setting (Yeang, 2006).

The thermal performance of the building envelope can make a significant contribution to decrease the needed energy. So, it is important to insulate the envelope of the building. The determination of the temperature of the walls that constitute the building envelope may be considered as an essential part of an efficient building design. The thermal performance of an opaque wall depends on how well its materials transfer the heat flux through it, and the weather conditions (Bellahcene et al., 2017). The building envelopes propose an essential element between occupied building spaces and weather conditions. Thermal insulation in the walls is often designed for static performance based on its thermal resistance (Karlsson et al., 2013).

The influence of outdoor climate on indoor climate, especially during summer, has been well investigated (Quinn et al., 2014). Indoor temperature is mainly influenced by outdoor, but its diurnal course is inhibited due to the physical characteristics of the building (Höppe, 1993). When direct solar radiation enters a room through the windows, the additional thermal load needs to be considered (La Gennusa et al., 2005). Studies by, for example, Höppe (1993) and Melikov et al. (2013) indicate that air velocity influences the convective heat transfer and therefore improves the thermal sensation, especially at high room temperatures and humidity levels.

High average air temperature and solar radiation during the summer indicate that cooling demand would be dominant. Abundant wind around the year offers a great potential for passive cooling and indoor air quality improvement (Fleury, 1980; Bahadori, 1986).

Passive cooling includes techniques for solar and heat control, heat modulation and heat dissipation using naturally driven phenomena such as natural ventilation, radiative cooling, evaporative cooling and ground cooling (Cook, 1990; Santamouris & Kolokotsa, 2013). It is useful for improving thermal comfort in low-energy buildings. Since cooling efficiency of passive techniques is closely associated with environmental conditions, local vernacular architecture has become invaluable reference in recent studies (Kimura, 1994). Problems and principles of passive cooling and application in agricultural buildings are solved in several studies (Conti et al., 2016; Týbl & Kic, 2016; Kic, 2017; Leso et al., 2017).

Based on these results and those of further studies, the assessment and improvment of indoor climate condition, especially temperature cause by solar radiation and convective heat transfer should be more considered.

The aim of the calculation method used in this paper is to analyze the indoor conditions in large simple buildings for workers during some days in the summer. We carried out inside and outside measurement of temperature humidity and light intensity. The places of measurement are two workshops which have similar dimensions but different roof windows and wall windows. The results of measurement will show the influence of solar radiation on the inside temperature in the different constructions of the buildings. Afterwards we can compare internal climate conditions to recommended values to evaluate how the roof and wall windows influence on the temperature and intensity of illuminance in the two workshops. The next part of this research paper is to set up formulas in order to calculate the demand of power for the air cooling to reduce the indoor temperature or intensity of air flow to maintain the same inside and outside temperature.

MATERIALS AND METHODS

The authors carried out experiments of measuring the indoor temperature at level of working place which is 1.1 m, in two similar large workshops with floor area 260 m^2 and height 6.5 m, during several hot summer days. The indoor conditions were strongly influenced by the solar radiation as the buildings have large wall and roof windows. The first building (WS1) has 54 m^2 of wall windows and 81 m^2 of roof windows, the second building (WS2) has only 34 m^2 of wall windows and 28.5 m^2 of roof windows.

Air temperatures and relative humidity were measured by data loggers Comet System ZTH65 outside and inside the buildings with registration at intervals of 15 minutes during ten days (long-time measurement). Parameters of ZTH65 are: temperature operative range –30 to +70 °C with accuracy ± 0.4 °C and operative range of relative humidity 5–95% with accuracy ± 2.5%.

During the long-measurement in the two workshops, natural ventilation and forced ventilation were not used; the workshops did not have air conditioning. Therefore, the inside temperature in the two workshops is always higher than outside temperature. In this search work, we set up formulas in order to calculate the required cooling power in the recommended values in relevant standards and supply air flow to keep inside temperature at the level of outside temperature.

For calculation of the required cooling power we use the following heat balance general equation:

$$Q_s + Q_w - Q_c = Q_a \tag{1}$$

where Q_s – total heat gain by solar radiation, W; Q_c – total heat loss by convection, W; Q_w – total heat gain through the walls, W; Q_a – power consumption of air conditioning, W.

We calculated the required supply air flow by the following general equation:

$$Q_s + Q_w - Q_c = Q_v \tag{2}$$

$$V_{air} = \frac{Q_v}{\rho \cdot C \cdot (t_i - t_e)} \cdot 3{,}600 \tag{3}$$

where Q_v – energy loss with ventilation, W; V_{air} – required supply air flow, $m^3\ h^{-1}$; ρ – density of the air, $kg\ m^{-3}$; C – specific heat capacity of the air, $J\ kg^{-1} \cdot K^{-1}$; t_i – internal temperature, °C; t_e – temperature of the supply air, °C.

We set up the Eqs (1), (2) and (3) in the program Mathcad and then we put measurement's data of construction and data in weather station to the equations. We showed obtained results in the graphs below.

We also evaluate the light in the two workshops by using daylight factor. The different translucent area of buildings resulted in different daylight factors, which were measured by lux meter TECPEL 536. The daylight factor is visual and light condition in interior. It shows the quantitative criterion of luminous state of the environment. The daylight can be calculated according to the Eq. (4).

$$e = \frac{E_m}{E_H} \cdot 100 \tag{4}$$

where e – daylight factor, %; E_m – illuminance of the given plane in the interior, lx; E_H – simultaneous unshadowed external horizontal illuminance, lx.

The obtained results of air temperature and relative humidity as well as the daylight measurements were processed by Excel software and verified by statistical software Statistica 12 *(ANOVA* and *TUKEY HSD Test*) to recognise if the differences between the results in both workshops are significant. Different superscript letters (*a, b*) in common are significantly different from each other in the columns of the tables *(ANOVA; Tukey HSD Test;* $P \leq 0.05$*)*, e.g. if there are the same superscript letters in the columns (workshops WS1 and WS2) it means the differences between the values in workshops are not statistically significant at the significance level of *0.05*.

RESULTS AND DISCUSSION

The measurement results in research work show and analyse outdoor and indoor temperature together with relative humidity of the air in the two workshop buildings during the summer when the rooms were without ventilation and air conditioning. Then, the obtained results were compared with the values recommended in relevant standards.

The results of long-time measurement of temperature and relative humidity of the air in the two workshops are presented in Table 1. The average external temperature was 18.7 ± 4.4 °C, average external relative humidity was 53.4 ± 16.6% during research period.

The results of this measurement show that the differences between both workshops in terms of internal air temperature as well as relative humidity are statistically significant at the significance level of *0.05* during the research period.

Table 1. Results of measurement and statistical evaluation of internal temperature t_i, internal relative humidity RH_i in workshops WS1, WS2. Different letters (*a, b*) in the superscript are the sign of high significant difference (*ANOVA; Tukey HSD Test*; *P ≤ 0.05*) between the conditions in the workshops

Parameter	Workshop	
	WS1	WS2
t_i ± SD, °C	31.8 ± 2.8^a	25.6 ± 1.6^b
RH_i ± SD, %	28.6 ± 3.5^a	36.5 ± 3.9^b

SD – Standard deviation.

The air temperature in the two workshops during the whole measured period and the temperatures in both workshops are higher than outdoor temperatures (the average temperature was 18.7 °C outside, 25.6 °C in WS2, 31.8 °C in WS1). The optimal temperature for workers in the summer is between 23 to 26 °C, which has not been reached in this period even during the external outdoor temperature. It shows that in the summer, when the workshop does not have ventilation or the cooling power, working place influences the heat stress for workers in the WS2.

From the measurement results, the air temperature in the WS2 is lower than in the WS1. The reduction of roof windows area and the improvement of the shape of windows in the WS2, contribute to reduce the impact of solar radiation on the indoor thermal comfort and reduce the inside temperature during the highest external temperatures. This construction in the WS2 would help to reduce the heat stress for workers.

Average values and standard deviation show that the relative humidity in the WS1 and WS2 is lower and more stable than outside. As in other building, the air moisture does not cause major problems in terms of microclimatic comfort. Recommended maximum relative humidity 70% was not exceeded in the two workshops. It is good for workers and for equipment. The minimal recommended indoor relative humidity is 30%. The low relative humidity 28.6% in the workshop WS1 is below this recommended value. It corresponds with the psychometric changes of the air inside the workshop with very high internal temperature.

For the next comparison of temperature values, the external temperature and temperature in the two workshops during 24 hours of the day are summarized in Fig. 1.

From the Fig. 1 we can see that, the highest temperature in the two workshops is from 2 pm to 5 pm which is around 1 hour later than the highest outside temperature. Then the temperature in the night (from 8 pm to 6 am) is lower because the solar radiation didn't impact the workshops. This two phenomena happened by heat accumulation from the walls, floor and roof of the building. Outside air temperature decreased but construction of this building released energy from day temperature. Therefore, the inside temperature is always higher than outside.

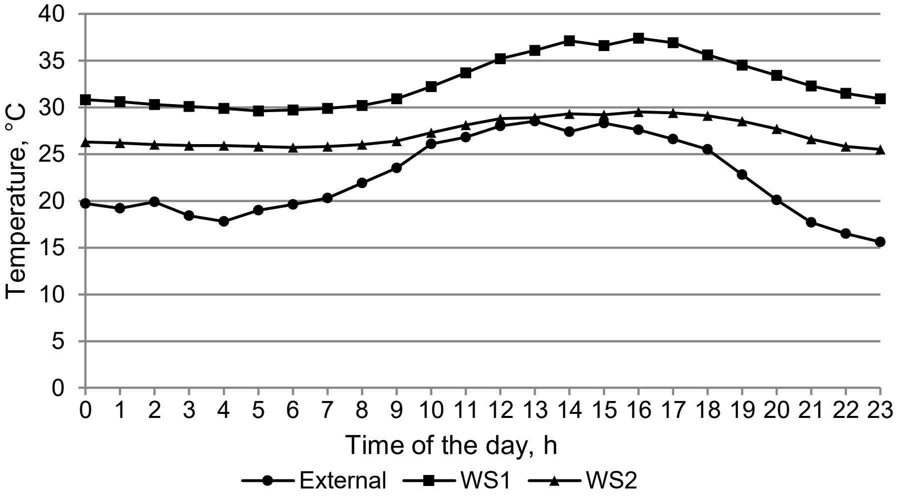

Figure 1. External temperature and temperature in the two workshops during 24 hours of the day.

In this case, we can use air conditioning equipment or forced ventilation to reduce inside temperature to the standard values. By calculation of energy balance, we can calculate the required cooling power or required forced ventilation in two workshops. The calculated results are showed in the Figs 2 and 3.

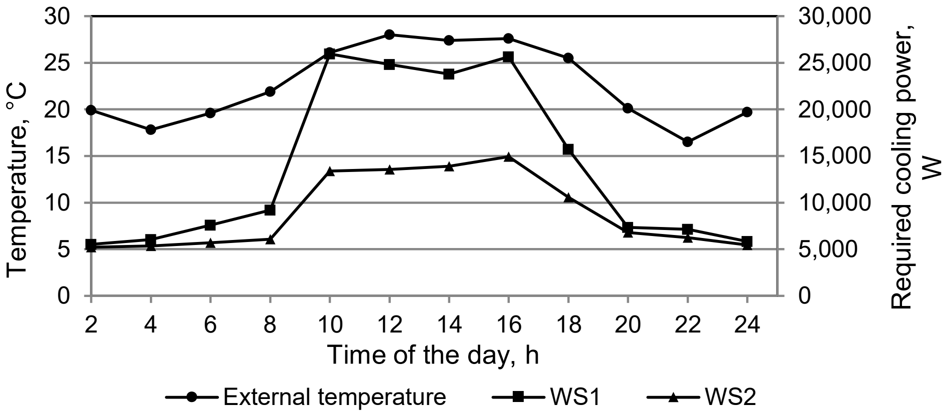

Figure 2. External temperature and required cooling power in the two workshops during 24 hours of the day.

In Fig. 2 is showed the required cooling power to keep inside temperature at 25 °C. In this case, the required cooling power in the WS1 is higher than in WS2 about 11 kW at the extreme outside temperature (between 12 am to 4 pm). From the night to the morning, the required cooling power decreases gradually and is nearly the same in two workshops.

In case of calculation of required ventilation to keep the same temperature inside and outside and to evacuate heat gain, the obtained results are showed in the Fig. 3. At the extreme outside temperature, the required ventilation in the WS2 is higher than in the WS1. The reason is because of the (3) equation. In this time, the outside temperature is 28 °C and the inside is 28.8 °C, therefore the temperature difference is only about 0.8 °C. It shows that, when the temperature of supply air and exhaust air is similar, we have to use the big intensive ventilation to decrease inside temperature. Therefore, we should not use forced ventilation when temperature of supply air and exhaust air are similar.

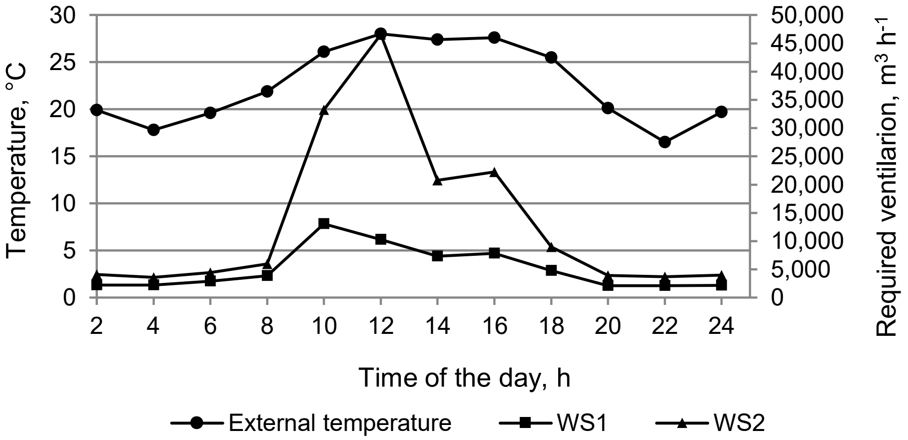

Figure 3. External temperature and required ventilation in the two workshops during 24 hours of the day.

The comparison of both workshops from the point of view of area covered by the roof windows and wall windows and measured values of illuminance in two workshops and calculated daylight factors e are presented in the Table 2. During the time of illuminance's measurement, the average measured simultaneous non shaded external horizontal illuminance E_H was approximately 27,000 lx.

Table 2. Results of measurement of the illuminance and calculated daylight factor e in two workshops WS1, WS2 during the short time with the area of roof and wall windows. The same letter (*a*) in the superscript is the sign that there is not high significant difference (*ANOVA; Tukey HSD Test*; *P ≤ 0.05*) between the daylight factors in the workshops

	Area of the roof windows m^2	Area of the wall windows m^2	Average measured illuminance lx ± SD	Daylight factor e % ± SD
WS1	81	54	2,491 ± 1,451	9.2 ± 5.4[a]
WS2	28.5	34	1,590 ± 1,435	5.9 ± 5.3[a]

SD – Standard deviation.

The average daylight factor e = 9.2% in the workshop WS1 is bigger than e = 5.9%. The difference between the daylight factors was evaluated statistically and surprisingly the difference is not significant at the significance level of *0.05*. It can be explained by the large standard deviations of the measured values of illuminance.

The mean daylight factor in the first workshop was 9.2% and in the second workshop 5.9%. According to the visual activity class IV in both workshops demanded daylight factor is 5%. The area of roof window of the WS2 is smaller than in WS1, therefore average measured illuminance in the WS2 is lower than in the WS1. We can say that, in the case of no air conditioning or ventilation, if the area of roof window decreases, temperature also decreases and the intensity of illuminance is lower, nevertheless not significantly.

CONCLUSIONS

Solar radiation is the main factor that influences the inside temperature in the two workshops. The temperature in WS2 is lower than in WS1 because the WS1 has bigger roof and wall window that absorb solar radiation and makes heat higher inside the building.

In the building WS1, when the inside air was not cooled or ventilated, the inside temperature (average 31.7 °C) exceeded recommended temperature (between 23 °C to 26 °C). This produces heat stress for workers inside the workshop.

In the night-time, the roof did not absorb solar radiation, however the inside temperature was still higher than outside. The reason for this phenomenon is the heat accumulation in the walls, roof, floor and all equipment in the workshops. These absorb heat in the day-time, and during the night release heat increasing air temperature inside the building.

The calculated power demand for the air cooling to reduce the indoor temperature to 25 °C is 25.6 kW in the first building, the cooling power for second building is 14,9 kW. The construction properties of the WP2 allow saving energy consumption for air conditioning or ventilation, but at the same time cause the increase of required energy for illuminance.

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