COOLING DEMAND IN MUSEUM PREMISES – NUMERICAL PREDICTION AND MEASUREMENT VALIDATION

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Abstract
The paper presents the results of identification and assessment of the energy demand for cooling purposes in the museum building. The analysis of cooling demand and assessment of indoor air quality were performed by the simulation analysis and validated by the measurement campaign of the indoor air quality in the building under consideration. For the purpose of thermal analysis the IDA ICE software was used. All simulations were carried out using meteorological data recorded by the local weather station. The results of the study indicate the necessity to use cooling in the museum premises. Presented analysis of the heat loads, which can occur in the exhibition rooms, can be helpful in making the decision about the installation of air conditioning systems in the museum, especially when thermal renovation of the building is planned. Such system can guarantee proper protection of the exhibits as well as thermal comfort for visitors.

Streszczenie
Artykuł przedstawia wyniki wielowariantowej analizy i oceny zapotrzebowania energii na cele chłodzenia w wybranym budynku muzeum. Analizy zapotrzebowania na chłód i oceny jakości powietrza wewnętrznego przeprowadzono na bazie symulacji komputerowej wykorzystując do tego celu program IDA ICE. Model obejmujący sale wystawowe został zwalidowany i dopasowany na podstawie danych pomiarowych parametrów środowiska wewnętrznego. Wszystkie obliczenia przeprowadzono w oparciu o dane meteorologiczne zarejestrowane przez lokalną stację meteo. Symulacje wykazały potrzebę chłodzenia sal wystawowych w okresie letnim. Zaprezentowane analizy obciążeń cieplnych w salach wystawowych mogą być pomocne przy podejmowaniu decyzji w spawie instalacji systemu klimatyzacji, który będzie gwarantować właściwą ochronę eksponatów, jak również komfort cieplny osób zwiedzających, szczególnie w przypadku planowania termomodernizacji budynku.

Keywords: **Museum microclimate; Energy demand; Indoor air quality; Simulation methods.**

1. INTRODUCTION

Indoor air quality (IAQ) is one of the factors, which decide on the safety of exhibitions located in museum buildings. Parameters such as indoor air temperature, relative humidity and solar radiation must be maintained within certain limits, dependent on the type of exhibits [1]. However, note that museums collect the objects made of different types of materials, therefore it is difficult to choose air parameters appropriate for all exhibits.

The standard concerning protection of cultural goods [2] does not define particular parameters of internal environment, it only suggests the methodology of conduct for the adoption of appropriate values based on "historical climate", i.e. such parameters of the environment which in longer period of time proved to be safe for certain types of collections. According to the indications of the standard frequent and significant fluctuations in temperature and relative air humidity are more dangerous for the exhibits than their absolute values.

Extensive and comprehensive analysis of the internal environment in historic buildings was presented by Camuffo [3]. The publication also emphasizes the impact of outdoor climate on condition of buildings generally comprehended under the concept of cultural heritage.

In general, recommended parameters are: internal air temperature of 15-25°C and relative humidity of 50% [4, 5]. Depending on the class of control, maintenance of temperature and relative humidity is required with a specified accuracy. For the highest class, the acceptable short-term deviations of humidity and temperature equal ±5% and ±2 K respectively. In the case of lower control class, limits are less strict and equal ±10% for relative humidity and ±5 K for temperature. ASHRAE Handbook Fundamentals also suggests the admissible seasonal deviations of these parameters [6].

On the other hand, comfort of visitors may be in contradiction with the optimal – for the exhibition – IAQ in museum premises [4, 7]. Museum buildings are also public buildings visited by substantial number of people, as well as places of work of some people. The survey conducted among visitors to the exhibitions at thirty museums [8] also point factors (other than microclimate) affecting the perception and evaluation of museum exhibitions. Factor analysis of the survey results showed that the ambient environment is a decisive factor for the perception and satisfaction of the visitors, however, not only thermal comfort, but also physical factors such as noise, number of visitors to the exhibition at the same time and even rest area are significant. These are the factors of rather sociological nature and emotional affect, than concerning technical solutions that create indoor climate, and will not be considered in this paper.

Most of the museums are located in historic buildings, in which technical solutions often do not comply with current requirements. There are usually only central heating system and natural ventilation in these facilities, which do not provide suitable conditions for the storage of exhibits. The difficulties in ensuring proper IAQ in museums result from historical value of these buildings, and, because of their heritage importance, there is no permission for any rebuilding or reconstruction of them.

The most beneficial for a museum microclimate is installing air conditioning system in a building. Thanks to such solution, maintenance, regulation and control of air parameters in premises are possible. This provides also proper level of thermal-hygrometric conditions in museum premises, both for the safety of exhibits and thermal comfort perception of visitors. Methods of numerical simulation, that provide the ability to compare the energy consumption for different solutions, may be helpful in proper selection of air conditioning and ventilation solutions [9, 10, 11, 12]. The aim is to obtain homogeneous microclimate of premises through appropriately selected air treatment equipment and control devices. Air conditioning system in a museum must be designed in a way providing proper functioning under different heat loads. Heat gains occurring in this type of facilities may radically change, causing significant fluctuations in temperature and relative humidity. This is confirmed by the measurements of internal environment parameters conducted in various museums [13, 14].

During one working day, a museum may be visited by several sightseeing groups, as well as by barely several people. Presence of people in a museum requires turning on the lighting. In most of the museums, the lighting is turned on only during the presence of visitors. Prior to designing the installation, the designer is obliged to collect detailed information about the museum collection, to find data on indoor climate suitable for the type of material, and to discuss the choice and to comply the advices of the custodian of the exhibition.

In order to provide the maintenance of constant air parameters round the clock, it is necessary that air conditioning system works not only during the opening to the visitors, but also when the facility is closed, as well as during the night. Nevertheless, it should be taken into account that full air conditioning is not always capable of maintaining established air parameters of the environment, especially in case of very variable heat load during the day and poorly designed air division. Variable number of visitors, their concentration, unstable outdoor air conditions and therefore variable heat and humidity gains in a short time period, usually limit the regulatory technique [15].

Introduction of air-conditioning system increases the cost of building maintenance, but certain strategies can reduce the cost of the use of the HVAC systems [16]. Museum buildings are usually budgetary units with very restricted sources of funding.

The study was undertaken to assess the demand for cooling power in the museum building, in which (only in one exhibition room) simple cooling system based on fan coils was installed. Realization of a series of variant simulations for different thermal loads may be a good basis for preliminary assessment of the need for cooling power required to maintain proper parameters of internal environment in all halls and for making investment decisions by the manager of the building.

Simulations refer to one specific museum. However, since the problem of a proper cooling is quite frequent, the simulation results can be helpful for the assessment of cooling needs of similar facilities. The simulation results presented here were validated based on the data collected during one year campaign [11]. The first aim of the investigation was the identification of the main parameters of indoor air quality in the exhibition halls – such as air temperature and humidity and CO_2 concentration level, for different internal heat gains, which can occur there in the summer – with the use of simulation methods. The second goal was the assessment, also through simulation, of cooling demand required to achieve the acceptable indoor air temperature in particular halls. For all cases of simulations, the Fanger's indices (PMV and PPD) were calculated [17], presenting thermal comfort of occupants.

2. BUILDING DESCRIPTION

The building under consideration was built in the beginning of the 20th century as a museum. It is a five-storey, double-winged building comprising exhibition halls, storage rooms, offices and laboratories. Exhibition rooms are located on the first, the second and the third floor (Fig. 3). The exhibitions' areas are: temporary exhibition (first floor) – 170 m^2, flora and fauna (first floor) – 250 m^2 (section 1) and 230 m^3 (section 2), ethnography (second floor) – 860 m^2 and painting hall (third floor) – 630 m^2. The height of exhibition rooms is about 3.6 m.

The building has mixed walls construction – partly made of reinforced concrete and partly of bricks. Thermal insulation of external walls is below current requirements: the value of U coefficient for walls differs for particular walls and is around 1.5 W/(m^2K) for the walls built from bricks and 2.5 W/(m^2K) for the walls made of ferroconcrete. Heat transfer coefficient for windows (frames and glasses) is between 1.6 and 2.9 W/(m^2K), and depends on the type of windows (metal, wooden or PVC).

Ventilation in the whole building is realized only by the air infiltration and exfiltration through the window cracks. It results in very poor air exchange rate in particular rooms. Originally the building was equipped with a mechanical ventilation system. After World War II, the obsolete and not modernized system was liquidated and was not replaced by any new system. Currently the whole ventilation of the building is maintained only by the infiltration mode. Nevertheless, several fan-coils are installed in the painting hall on the third floor with the intention of decreasing the air temperature in summer. Unfortunately, these devices work only with recirculated air, this is why they do not improve ventilation in the hall.

In order to check current conditions for conservation of collections in the museum one-year continuous measurement of the main indoor environment parameters was carried out. Such parameters as air temperature, humidity and CO_2 concentration were recorded in four museum premises. Detailed description of the experiment and its results are presented in [11]. Fig. 1 and 2 present variation of hourly values of internal air temperature and relative humidity during the period from June to August, recorded by selected sensors placed in particular exhibition halls.

Lack of proper installations creating microclimate in analyzed museum and lack of automatic control in existing installations prevent from formation and maintenance of temperature and humidity values within proper limits. Significant daily fluctuations in the parameters of internal microclimate can be observed. Relative air humidity and temperature are strongly dependent on external conditions. The measurements showed that due to the heat accumulation of a building, in which walls play important role, changes of internal temperature are slower and of smaller amplitudes. Air temperature is more stabilised at the exhibition of painting due to installed fan-coils which locally reduce air temperature. Maximum values of temperature (even above 30°C) for non-air-conditioned premises were recorded in July. Maximum values of relative humidity (65-75%) were recorded for most of the premises in September.

Thanks to the set of the data, the simulation model could be validated and tuned, creating a reliable tool to predict and asses the energy consumption and IAQ for different operation modes of simulation.

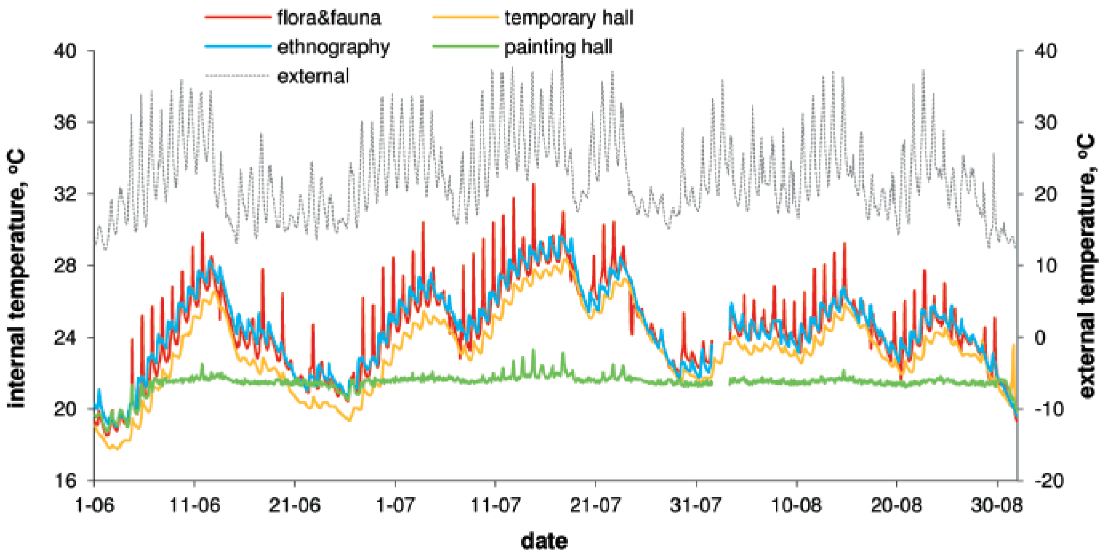

Figure 1.
Variation of internal air temperature over time in the exhibition halls

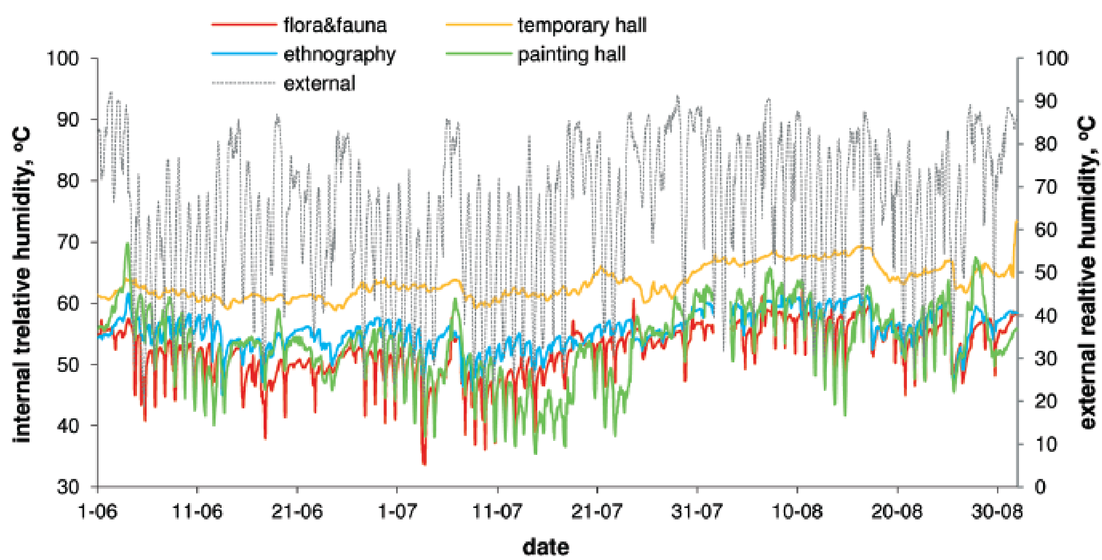

Figure 2.
Variation of internal relative humidity in the exhibition halls over time

3. METHODS AND SIMULATION MODEL

The analysis of the energy demand and assessment of the indoor air quality were both performed through numerical simulation. For the purpose of thermal analysis, the IDA ICE 4.22 software was used [18]. The program enables to create and solve heat balance equations for all simulated zones. Thus, the following heat fluxes were calculated during simulation:

- heat fluxes through the external and internal partitions (walls, floors, windows) due to air and surface temperatures and climate data,
- heat from air flows,
- internal heat gains from occupants (including latent heat) and electrical lighting,
- heat from room cooling units,
- direct solar radiation,
- heat from window surfaces (including absorbed solar radiation),
- heat from walls and floors (heat stored in the structure).

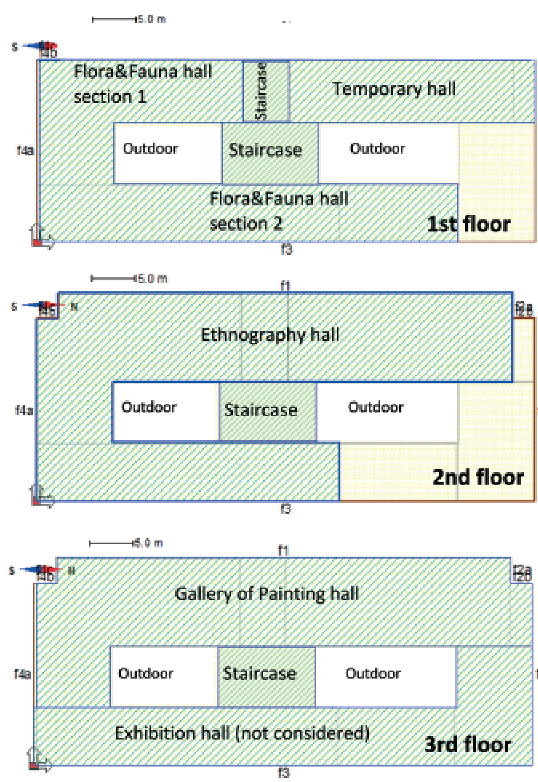

Figure 3.
IDA-ICE numerical model for the exhibition halls

Apart from the objects listed above, variability of air temperature, air changes per hour, relative humidity, PMV and PPD indices, and the details of energy used by cooling units were also calculated by the IDA code.

Numerical model of the museum building was built taking into account only the exhibition halls and staircase while the rest of the rooms (store rooms, cubby-holes and other auxiliary rooms) were omitted (Fig. 3).

All simulations were performed in a summer time, because the aim of the study was the assessment of cooling demand, at one-hour time step. Three warmest months were taken into account: June, July and August. The local weather station provided the set of meteorological data necessary for the period of simulations.

4. MODEL VALIDATION

The first run of simulation was performed to test the numerical model of the museum and to tune it based on the measurement of the air temperature in particular premises of the museum. The main assumptions of the simulation were as follow:

- free floating of the air temperature in all simulated zones;
- the air change rate in all exhibition halls: 0.3 h^{-1} (there was no detailed data on the air change, but the measurements based on the CO_2 concentration decay and air flow simulations show that the air change rate does not exceed this value [12, 19]);
- no internal heat gains in the museum halls (summer was chosen for the period of the simulation for validation purposes, because internal heat gains in

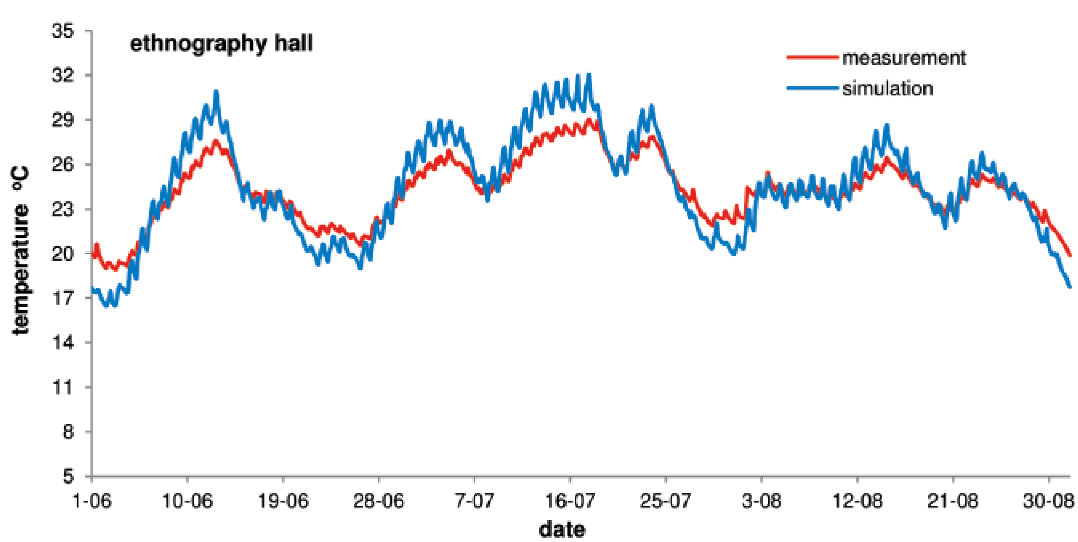

Figure 4.
Comparison of the air temperature – measured and simulated (hourly values) in the ethnography hall

Table 1.
Comparison of the results of the measurement and simulation of air temperature (hourly values) in the museum premises (June – August)

Exhibition room	Mean air temp. [°C]		Maximum air temp. [°C]		Correlation coefficient
	measurement	simulation	measurement	simulation	
temporary hall	23.29	23.89	28.36	32.14	0.946
flora and fauna	24.41	24.53	32.53	32.71	0.951
ethnography	24.24	24.47	29.04	32.02	0.976

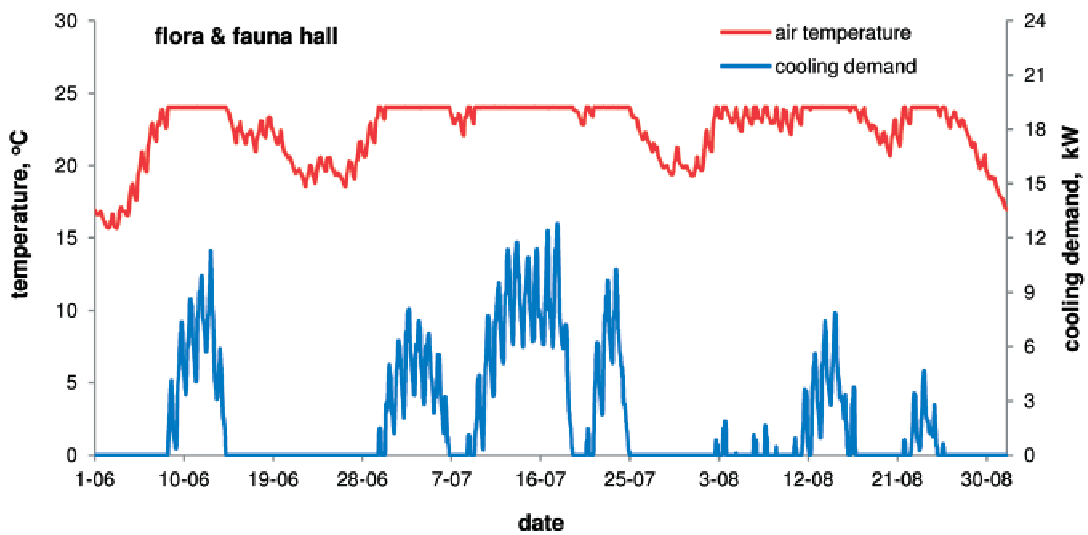

Figure 5.
Variation of indoor air temperature and actual power for cooling over time in the flora and fauna hall

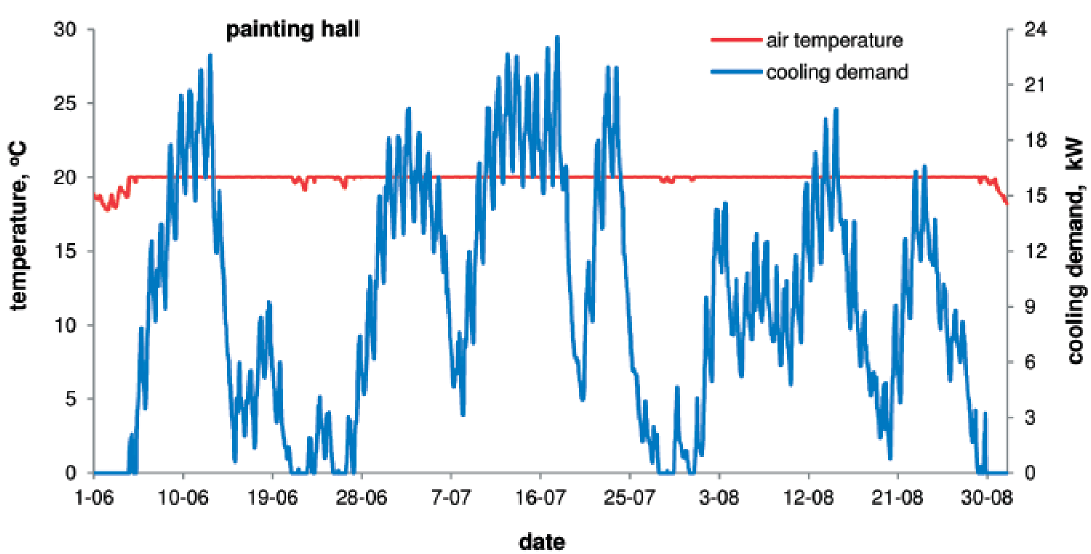

Figure 6.
Variation of indoor air temperature and actual power for cooling over time in the painting hall

the museum at that time were minimal; the reason is the lack of school tours – school holidays and less of other visitors);

- all windows completely curtained (solar radiation maximally limited);
- weather data recorded by the local station;
- simulation performed with one-hour time step.

When comparing the course of the air temperature variation obtained by measurement and simulation, the results of the simulation look very reliable. Fig. 4 presents the example of free floating air temperature (measured and simulated) in the ethnography exhibition room located on the second floor of the building. It can be observed that the courses of indoor air temperature for measurement and simulation are very close – the correlation coefficient is about 0.98.

The results for other museum exhibition rooms are very similar. Table 1 gives the details of the comparison of the simulation and measurement results.

Although mean air temperature is very close to the proper value for the museum exhibitions, its maximum reaches even 32°C, exceeding the required value of the maximum air temperature in all rooms (24°C) during the significant time under investigation (summer time).

The other conclusion from the numerical experiment is more valid: pearson's correlation coefficient assures that the numerical model of the museum premises, built in the IDA-ICE software, is reliable and can be used as a tool for investigation of different thermal behaviors of the building under consideration.

5. SIMULATIONS AND RESULTS

The series of simulations were performed with the certain assumptions. Constant air temperature was assumed for all exhibition rooms: 20°C for painting hall and 24°C for temporary, flora and fauna and ethnography halls. Cooling in all of these halls was realized by the ideal coolers. In the staircase free floating air temperature was assumed. In all rooms, constant air change rate was set at 0.3 ACH thanks to natural ventilation (infiltration).

Measurements showed that considering the current condition of the building, from June to August, the temperature of 20°C is exceeded in the painting hall during 95% of the time, the temperature of 24°C – in the temporary hall within 36% of the time, in the flora and fauna hall within 57% of the time and in the ethnography hall within 31% of time.

5.1. Cooling demand

Internal heat gains (resulting from lighting and metabolic heat generated by occupants) were taken into account according to four main variants of simulations:

- v.1 – no internal heat gains;
- v.2 – only full lighting in rooms, no visitors;
- v.3 – full lighting, 10 people in every exhibition rooms;
- v.4 – full lighting, 50 people in every exhibition rooms.

The power of lighting was assumed according to the inventory of the equipment in particular rooms. Installed power differs significantly in particular exhibition rooms, and equals:

- temporary hall – 5400 W (32.7 W/m^2);
- flora and fauna room – 600 W (1.3 W/m^2);
- ethnography room – 1000 W (1.1 W/m^2);
- painting hall – 17000 W (26.2 W/m^2).

The number of visitors derives from the survey carried out in the museum. Mean number of visitors could be assumed as 10 people and maximum would not exceed 50 people per room. Heat gains in zones were taken into account according to the declared schedule for the presence of people and turning on the light: 8-12 and 13-17 hours on weekdays. This schedule is not fully credible, but it is impossible to predict the number of visitors and time of their presence precisely, thus the schedule was taken according to the hours of opening of the museum.

The results for the first variant (v.1) of simulation, which balanced heat fluxes without internal heat gains, are presented in Fig. 5 and 6. It can be noticed that the necessity of the maintenance of the internal air temperature in the painting room equal to 20°C, increases the cooling power significantly (even twice – Fig. 6) when compared with the requested air temperature in other halls (24°C – Fig. 5).

Seasonal rate of cooling demand (June-August) for different variants of internal heat gains in the museum premises is presented in Fig. 7. The smallest room (the temporary hall) needs relatively more energy for cooling when heat gains increase. It results from their small volume loaded by large number of visitors (variant 4). For the same heat gains, cooling demand in the painting room in general is greater than in other halls. It can be explained by the set point of the air temperature for cooling, equal to 20°C (when the setting in other rooms equals 24°C).

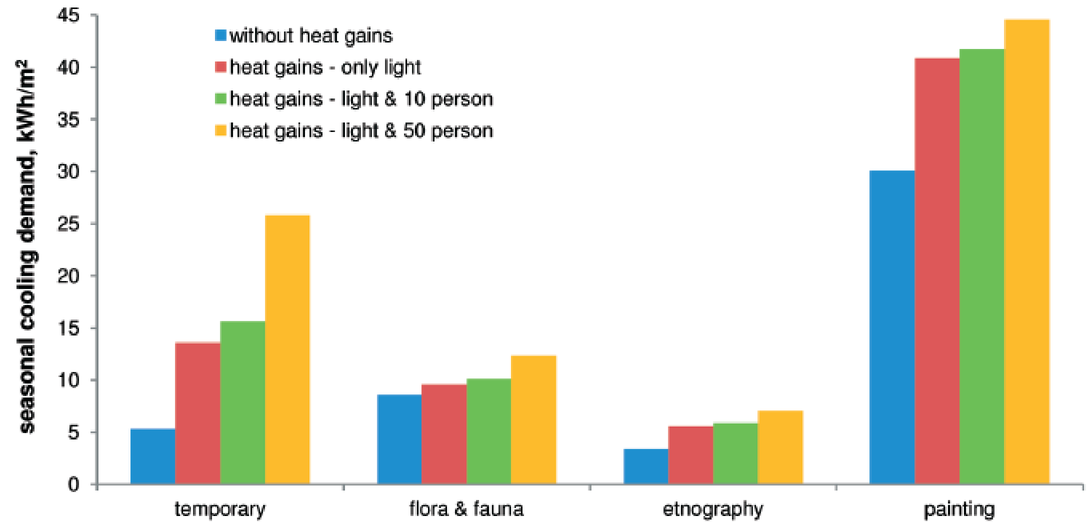

Figure 7.
Rate of cooling demand (from June to August) for different variants of internal heat gains in the museum premises

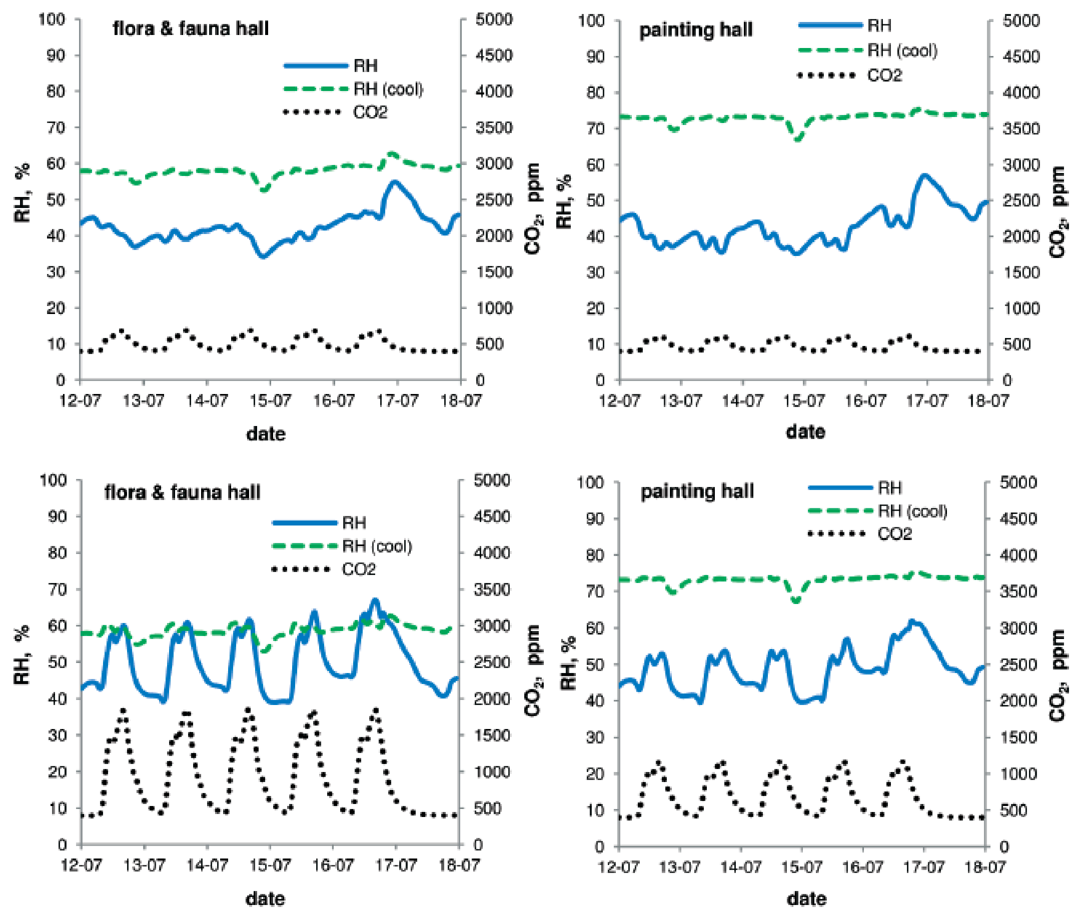

Figure 8.
Changes in relative humidity and CO_2 concentration for one week of July for average heat gains (variant 3) – at the top and maximum heat gains (variant 4) – at the bottom

The additional simulation was performed to find the reasons for the results of greater cooling demand in the painting hall. The results show that when the same set point of the air temperature for cooling, equal to 24°C, was declared in the painting room (like in other zones), the value of power demand for cooling in this room was comparable to other rooms (~9 kWh/m^2 for variant without heat gains). It means that large cooling demand in this room results from the value of the set point of cooling devices being activated at 20°C. The other reason is a big value of heat gains from the lighting (installed light power in the painting room is about 17 kW).

5.2. Indoor environment quality

The assessment of the indoor air quality in the museum premises was based on the calculation (by the IDA-ICE software) of basic parameters in the declared zones, such as:

- indoor air temperature,
- relative air humidity,
- Fanger's comfort indices (PMV and PPD),
- air change rate (ACH),
- CO_2 concentration level.

Parameters listed above depend not only on the cooling level, but also on the ventilation of the premises. The air change rate was assumed as 0.3 ACH in all zones. The other parameters varied over time. The simulation results are presented for two halls: the flora and fauna exhibition room (on the first floor) and the painting hall (on the third floor). All simulations for this case were performed with the assumption of presence of occupants for two variants: 10 people (v.3) and 50 people (v.4).

When cooling is not available, indoor air temperature reaches even more than 30°C in the halls (Fig. 1, 2 and 4). For the case of cooling of the premises, the air temperature is set and reaches 24°C (or 20°C in the painting hall) (Fig. 5 and 6). From the point of view of the exhibitions safety, the value of humidity ratio is more important than the temperature.

Relative air humidity strongly depends on air temperature in the premises and is a parameter important from the point of view of the safety of the exhibits. In the graphs (Fig. 8) significant fluctuations in the level of RH at high internal gains in case of no cooling can be observed. Admittedly the use of cooling causes an increase in relative air humidity, but what is more important, it remains on almost constant level, what is advantageous for the exhibitions.

Relative air humidity at the level of 70% in the hall with the painting exhibition may be considered as too high, but similar results were obtained in measurements carried out at the same time (see Fig. 2). Therefore suggesting by the indications of the EN15757 standard [2], such level of relative air humidity can be recognized as permissible as "historical climate". Reduction of relative air humidity would be possible in case of better ventilation of the premises. The air change rate, equal to 0.3 per hour (this assumption results from the measurement in the museum), is too small to remove the pollutants (CO_2 and moisture) from the museum rooms.

Improper level of the indoor air quality can be more uncomfortable for visitors. One of valuable indices of it can be the level of CO_2 concentration in the air [20, 21, 22]. This parameter was simulated for all zones of the museum. The variation of CO_2 concentration for one week of July (the warmest in the summer) is presented in Fig. 8.

When maximum heat gains are assumed for the rooms (the number of visitors equals 50 in every museum hall), CO_2 concentration reaches even more than 4500 ppm in the smallest room (temporary exhibition hall). In larger halls (e.g.: flora and fauna hall, Fig. 8) the level of CO_2 concentration can be acceptable for visitors, its maximum value does not exceed 2000 ppm and in average is less than 1000 ppm.

The level of CO_2 concentration does not depend on the air temperature in the room (in this case resulting from cooling). The most important factor is ventilation of the room. The same concerns relative air humidity, the level of which strongly depends on the premises ventilation. The air change rate, equal to 0.3 per hour (this assumption results from the measurement in the museum), is too small to remove the pollutants (CO_2 and moisture) from the museum rooms.

Comfort indices, PMV and PPD, calculated during simulation courses, were taken into account only when people were present in the rooms. Cumulative values of PMV for two exhibition halls for considered three summer months are presented in Fig. 9. Maximum heat gains were considered (variant 4) for two cases: for no cooling and for proper cooling.

The value of PMV index should be in the range of ±3 [23] and the optimal thermal comfort in rooms characterizes PMV between ±0.5. The PMV equal to 2 indicates that about 80% of occupants are dissatisfied with the environment. The results of the simulation performed when the cooling of the halls did not exist (Fig. 9) show that the thermal comfort in the

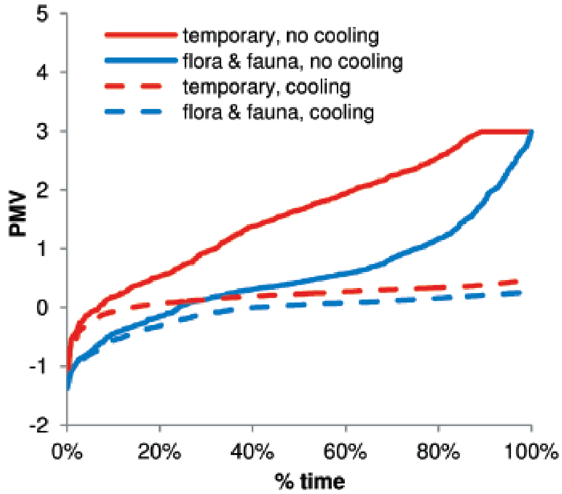

Figure 9.
Cumulative distribution of PMV indices in particular halls for maximum heat gains

temporary hall is on unacceptable level – much higher than +0.5 during about 70% of the considered time. The quality of thermal environment in the flora and fauna hall is better, but the level of +0.5 PMV is exceeded for about 30% of the time. These results confirm that, if the proper thermal comfort in the museum premises is required, cooling is necessary. Turning on the cooling, with proper cooling power installed, can create indoor environment in the museum halls on the level, which can be assessed as close to 0 PMV (Fig. 9).

6. COMMENTS AND CONCLUSIONS

Simulation methods are very useful when direct measurement is difficult or impossible. It concerns especially historical buildings, where conservator can always find a reason to prohibit the experiment and measurements.

Museum buildings usually differ from each other very much, and, because of their uniqueness, the assessment of IAQ and energy demand for cooling and heating requires individual treatment. In such cases, the strength of simulation methods is evident. However, it must be taken into account that the results of simulations are as reliable as they were positively validated on site in the considered building. In the case presented in this paper, such validation was performed by comparison of the measurement and simulated result of the course of air temperature in all main premises of the museum.

The main aim of this investigation was the assessment of the cooling demand in the museum halls to assure thermal comfort of visitors and safety of the exhibits. The obtained results show the scale of a problem and can be helpful for designer when cooling system will be installed in the museum.

Presented results of the study concern one specific museum building, but they allow the formulation of several general conclusions regarding similar facilities.

When the necessary cooling demand is calculated, maximum potential cooling demand in a given premises should be taken into account. Cooling demand results mainly from internal heat gains; in the considered case (museum premises) it means mainly the number of visitors, therefore maximum number of people was assumed.

There are some points of uncertainty in the simulation assumptions (e.g.: the schedule of heat gains in the halls, details of a weather data and so on) and the results obtained from the simulation can differ from real values, but they present proper range of the results (it is confirmed by the validation of simulation results by the measurement of indoor air temperature).

The obtained results give a possibility to assess the cooling/heating demand with taking into account the impact of particular factors influencing it. Based on the results of the same simulations, parameters of indoor environment can be estimated.

Continuous recording of temperature and relative air humidity in the museum halls, which will enable the observation of instantaneous and long-term changes, can be recommended.

Performed simulation very often revealed other phenomena and problems in the building, which were not the main aim of the investigation. Based on these results, some potential problems were indicated. The main problem in this building is lack of ventilation; the system of ventilation for the whole building does not exist in practice. It results in poor removal of contaminants (mainly moisture and CO_2) from the rooms of museum. It can cause visitors' malaise and, what perhaps is more important, the excess of moisture can be dangerous for the exhibitions.

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