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Internal environment in the museum building—Assessment and improvement of air exchange and its impact on energy demand for heating

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ABSTRACT

The paper presents the results of the analysis of the impact of various ventilation systems on the energy consumption performed for one Polish museum building that was built in 1929–1930. Simulations were carried out with the use of two computer codes: CONTAM and ESP-r. Multi-zone models including the exhibition rooms and the staircase were prepared. The simulations were made of synthetic weather data for one of the Polish towns for two months of the heating season. Twenty-four hour variability of internal heat gains was taken into account. The results show clearly that the natural ventilation system (which is currently used in the building) enables the air exchange with fresh air on the first floor only. The air infiltration on the upper levels is close to zero. Rebuilding the ventilation system generates changes in the energy demand of the building. It is presented how the heat demand increases with the increase of the ventilation air flow and what is the impact of the air infiltration on the heat demand for different variants of ventilation.

1. Introduction

Parameters of internal environment in buildings are strictly dependent on the function that these buildings perform. For general purpose premises such as apartments, offices, etc., determination of the requirements for internal air quality is precisely defined, for example by appropriate standards. In special purpose facilities, e.g. museums, the determination of desired or even necessary parameters of indoor environment is difficult and ambiguous. The established and maintained indoor environment parameters in the museum premises must be appropriate both to ensure proper conditions to prevent degradation of the objects due to external factors and to create comfortable indoor environment for visitors.

Three groups of threats to the museum collections can be distinguished:

- hygrothermal conditions of the environment,
- air pollution: dust, chemical, biological,
- excessive internal gains (lighting, heat and humidity gains from the people).

The level of threat posed by these factors is different for different types of collections. In some countries, especially in those with a large number of historic monuments, there are appropriate regulations determining optimum environmental factors for the protection of the exhibits on the museum premises [1,2]. Some guidance regarding the environmental conditions can be found in ASHRAE publications [3,4].

Removal of the above threats can be accomplished by various means, both through the use of appropriate technical solutions, e.g. dehumidification or humidification of museum rooms which are at risk, heating, cooling and air-conditioning of exhibition halls [5,6], as well as through the protection of the exhibits by the use of closed display cases, special display cassettes, etc. [7,8].

In order to determine the optimum microclimatic conditions in the exhibition halls it is necessary to assess the current state. The assessment is carried out by monitoring temperature and relative air humidity [9–12] as well as CO_2 concentration, the latter being an indicator used to evaluate heat gains from the visitors [13], and the quality of the ventilation in the building [14]. Particular attention should be paid to sharp peaks in temperature and air humidity, because instantaneous acute changes in these parameters are dangerous to the exhibits. As to other threats, the monitoring can be more sophisticated than simple tracking of changes in temperature and air humidity. This concerns especially the level of gaseous pollutants on the premises, monitoring of which requires advanced technologies [15].

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Fig. 1. The museum building selected for the analysis.

Ensuring proper parameters of indoor environment depends to a large extent on proper ventilation of the exhibition galleries. Appropriate level of air exchange allows both removing the excess of moisture and heat from the premises, and reducing air pollution. The optimal solution is to equip the museum premises with the air-conditioning system. The strategy for the use of the air-conditioning should be carefully planned. The way it is used should be optimal from the point of view both ensuring proper microclimatic conditions and energy saving. Many historical museum buildings are massive ones. The studies [16] show that night ventilation for cooling of such buildings in summer can be applied. When indoor and solar gains are accurately controlled and minimized, the synergic effect of high thermal mass of the building and nocturnal air ventilation allows maintaining appropriate conditions for the preservation of museum objects without the use of mechanical cooling system.

It should be noted that the use of the air-conditioning system may result in rapid changes in temperature and air humidity, which can be harmful to the exhibits in the exhibition rooms [9]. To develop an optimal strategy for the use of the air-conditioning, numerical simulations using building energy performance simulation codes [17–21] are useful.

In some cases, the improvement of the ventilation system is considerably impeded due to historic nature of the facilities and prohibition against any interference in the structure of the building. In some historic buildings there are architectural structures that can be considered as a kind of natural ventilation system [22]. Medieval buildings often have natural ventilation ducts which were deliberately constructed. In both cases, it makes sense to check the effectiveness of working of this kind of ventilation. Due to their nature, historical building offer limited possibilities for environmental conditions measurement. Consequently, one of the methods to evaluate the ventilation system is computer simulation [23].

The paper presents the results of numerical simulation of various ventilation systems which could be applied in one Polish museum where only natural ventilation currently occurs. The proposed ventilation systems were analysed in terms of air exchange and their impact on heat demand. The results of the study presented in the paper are only a part of larger project. The analyses of internal environment in terms of air temperature and humidity have been described in detail in a separate publication [20].

2. Description of the analyses

The museum located in Upper Silesia of Poland was selected for the analyses. It is double-winged five-storey building erected in 1929–1930 and was specially designed for exhibition purposes. The main entrance is in the west part of building (Fig. 1). The exhibition rooms are located on the first, second and third floors. The total exhibition area amounts to: 250 m^2 (Flora&Fauna exhibition) and 170 m^2 (Temporary exhibition) on the first floor, 860 m^2 on the second floor (Ethnography exhibition) and 630 m^2 on the third floor (Gallery of Painting). The height of exhibition rooms is about 3.6 m.

The building has mixed walls construction—made partly of reinforced concrete and partly of bricks. The building is equipped with various types of windows (wooden, aluminium, PVC). The window panes on the west side are covered with anti-reflection coating. Additional ways of protection from the sun at the exhibitions are internal blinds and plasterboard walls separating the room from external partitions. The building is equipped with the central heating system with radiators. There is the heating and cooling system with fan coils in the Gallery of Painting hall. The major disadvantage of this building is the lack of a ventilation system. Originally the building was equipped with a mechanical ventilation system. After World War II, the old-fashioned and not modernized system was dismantled but no new system was installed instead. Currently the whole ventilation of the building is provided by means of infiltration only.

The analysis was performed with the use of two computer codes: CONTAM, the programme designed for multi-zone analysis of the ventilation and indoor air quality in buildings [24]; and ESP-r, the energy simulation system which is capable of energy and fluid flows modelling [25]. Due to the aim and requirements of the study, it was decided to represent the building in the form of multi-zone macro-scale models. In such a model the building is represented as a series of idealized zones with constant parameters of air within the entire zone. The zones are connected with each other and with the external space by the flow paths of the air or heat that reflect the actual paths of the energy and mass exchange.

Two numerical models were built: the first one, CONTAM model, was used to simulate the ventilation air flow in the building. The results of the simulation were used as an input data in the second model—ESP-r thermal model. The zoning was assumed in both models, which was imposed by very complicated internal structure of the building. All simulations were performed with 1-h time step for weather data from the local meteorological station for the period from 1 January to 30 September 2010.

3. Simulation analysis of the air flow

Multi-zone numerical model of the museum, representing all identified air flow paths both infiltrating through the cracks of windows and doors as well as inter-zone air flows, was built. The model includes exhibition rooms on three floors and the whole staircase. The model did not include the ground floor (there is no connection between the ground floor and the part of the building that houses exhibitions, and thus there is no air flow path) and the rooms on the fifth floor (it is the unused part of the building connected with the staircase only through one closed door). The staircase was modelled from the level of the entrance to the exhibition area, up to the top floor of the building. The staircase located centrally in the building – having the nature of the atrium – is a potentially important path of air flow throughout the building. The staircase was modelled as a vertical series of zones connected by low resistance openings through the floors. Fig. 2 shows three levels of the museum building represented in the CONTAM program.

One of the biggest uncertainties was the value of the air infiltration coefficient, which describes air tightness of the windows. Air infiltration coefficients were adopted based on the literature data verified by the authors' own measurements [26,27]. After the model calibration the air infiltration coefficients were set as follows: PVC and wooden windows: $a = 0.2\ m^3/(m\ h\ Pa^{0.67})$, aluminium windows: $a = 0.5\ m^3/(m\ h\ Pa^{0.67})$, entrance door: $a = 1.0\ m^3/(m\ h\ Pa^{0.5})$, internal doors: $a = 1.5\ m^3/(m\ h\ Pa^{0.5})$. Temperature in the model was kept at 20 °C in exhibition rooms and 18 °C in corridors.