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Evaluation of thermal comfort in an historical Italian opera theatre by the calculation of the neutral comfort temperature

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ABSTRACT

Theatres are a very complex environment where thermal comfort is difficult to control. They frequently operate at high occupancy level and tend to have high sensible and latent heat loads. An application of the neutral comfort temperature methodology is proposed to analyze this particular kind of building. Thermal-hygrometric parameters defined in ISO 7730, Ashrae Standard 55/2004 and ISO 10551, were measured at carefully selected locations in the occupied zone within the auditorium in the Fraschini theatre, in order to ensure a good representation of human exposure to thermal comfort. In addition, a subjective evaluation was achieved by the distribution of a dedicated multiple response questionnaire. More than 400 questionnaires were analyzed, comprehensive of information for the application of the traditional static and adaptive model. When heating system is on (1st and 2nd survey), thermal stratification is really relevant in the theatre (air temperature runs from 23 °C in the stalls area to 30 °C in the upper order), while when the theatre is in naturally ventilated, the thermal stratification is not relevant. An application of a new thermal comfort evaluation method is here proposed by means of the calculation of the neutral comfort temperature with both the analytical and adaptive methods. . The methodology was also applied to data acquired in 9 different open space offices, where a total amount of 846 people were interviewed. Results showed that the method is applicable to both theatres and open plan offices and could provide a simple tool to quickly evaluate thermal comfort conditions.

1. Introduction

Theatres usually have high heat loads, which are of a transient nature as audiences come and go, and from lighting which changes from scenes to scenes, and also their occupancy can vary from completely full or nearly empty, depending on performances. Furthermore, unlike other building types, the use of opening windows for air intake and extract ventilation is not possible, requiring a different approach. Air must be distributed over a wide area, both within the auditorium and the stage, with numerous supplies and return registers. All these factors place constraints on the ventilation design, and if it is poor, it can led to the deterioration of indoor air quality and thermal comfort. There is some useful Literature on thermal comfort performance in theatres. A study of Papakonstantinou et al. [1] only based on computational fluid dynamics (CFD) modelling scenarios, evaluated how two ventilation systems with the same air inlet arrangement, but different systems of air extraction, affected the air speed, temperature and CO_2 concentration profile inside the teaching auditorium. The conclusion, not surprisingly, was that the lowest rate of air change leads to the increase of temperature. Furthermore, it was found that CO_2 concentration decreases rapidly if the ventilation rate is increased, in this case by the unexpectedly large factor of five. Another study, only based on computational fluid dynamics, was conducted by Stamau et al. [2], in order to evaluate thermal comfort conditions in the indoor stadium of the Galatsi Arena, which hosted the sports of rhythmic gymnastics and table tennis during the Olympic Games Athens 2004. Calculated PMV and PPD values showed that thermal conditions were very satisfactory for air temperature of 16 °C with a percentage minor of 7% of the spectators was expected to be slightly uncomfortable.

A more comprehensive assessment methodology was developed by Cheong and Lau [3], and applied to indoor air quality and

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thermal comfort in lecture theatres in Singapore. A questionnaire survey was carried out in the lecture theatre a few weeks prior to monitoring campaign. Despite the fact that all the thermal comfort parameters were within the range limit, the occupant survey showed that more than 20% of the occupants were not satisfied with thermal comfort. Furthermore, the authors concluded that the air conditioning system was unable to cope with the peak occupancy load.

Another review [4] focused on thermal comfort and indoor air quality in a lecture theatre with a 4-way cassette air conditioning and mixing ventilation system. This showed that increasing the discharge angle from the supply grilles on the cassette unit makes uniformity of thermal comfort worse, but rarely affects the indoor air quality. A very comprehensive evaluation was carried out by Kavgic et al. [5] on the thermal comfort and indoor air quality in the mechanically ventilated theatre of Belgrade. The analysis based on the results of monitoring and modelling as well as the assessment of comfort and health as perceived by occupants showed that the environmental parameters were within the standard limits. However the calculated ventilation rates showed that the theatre was over ventilated, which has serious consequences for energy consumptions, and the displacement ventilation arrangement employed led to higher than expected complains of cold discomfort, probably due to cold draughts around the occupants feet. The problem of air distribution in theatre was also recently developed by Cheng et al. [6], who presented simulation results for the design of a stratified air distribution system in a large space lecture theatre. Results revealed that the best satisfied thermal environment was obtained when supplied air from floor level, terrace and desk edge mounted grilles simultaneously. A specific underfloor air distribution (UFAD), which is typically just used in office buildings, was investigated for a huge theatre space with high ceiling by Kim et al. [7]. Considering the performance not only for energy saving but also for thermal quality, the UFAD system appears to offer many advantages, however additional research is needed on key variable, such as location and kind of diffusers, distance between diffusers, configuration of buildings and height in order to put the system into practise. The above scientific reviews show the great complexity for obtaining adequate comfort performance, both perceived and measured, in theatres. None of all the cited scientific works showed a simple method to quickly evaluate thermal comfort conditions in this particular type of environment.

Other papers consider thermal comfort studies in climate conditions focussing on other kind of buildings: DiasPereira et al. [8] studied the thermal comfort in a Portuguese class-room, Conceicao et al. [9] developed an adaptive comfort model in a kindergarten in Portugal, Asit Kumar Mishra et al. [10] proposed an adaptive thermal comfort model for the tropical climatic regions of India and Manu S. et al. [11] presented a single adaptive model for office buildings across India asserting its validity for both naturally ventilated and air-conditioned modes.

In the present study, in order to analyze the level of thermal comfort in a typical eighteen century Italian horseshoe shape theatre, with 5 orders balconies, a comprehensive evaluation study was carried out in the Fraschini theatre of the city of Pavia, in both mechanical and natural ventilated conditions. In addition the method of the neutral comfort temperature was applied to the theatre.

2. The Fraschini theatre

Thermal comfort in the Fraschini Theatre, located in the city of Pavia (Italy), was experimentally investigated. The construction of the building ended in 1773.

The plan surface is 340 square metres and its volume is 7200 cubic metres. The theatre has a typical Italian horseshoe shape with 5 orders balconies. In Fig. 1 the plan of the theatre is presented.

The building was object during the years of different actions of maintenance, but the most important restoration took place in 1985 and interested the whole theatre. Recently, in 2010, the wooden floorboards of the parterre were completely renewed and the internal surfaces of some balconies were restored, in order to regenerate the “marmorino” decorations.

In Fig. 2a and b interiors of the Fraschini theatre are shown.

The theatre has an air building service having a total power of 1220 kW and delivering 41,000 m^3/h of air. The heating of the parterre is provided by jet-nozzles diffusers situated in the fifth order of seats. The hot air is then recollected by grilles situated at every floor. In Fig. 3 is possible to see the nozzles and their position in the theatre.

3. Methodology

Thermal comfort in the Fraschini theatre was evaluated with analytical-objective method by means of experimental surveys and questionnaires, in order to obtain information about the subjective perception of the audience.

3.1. Questionnaire surveys

The questionnaire given to the audience was very similar the one used by Buratti et al. and Nematchoua et al. [12–16], which comply with ISO 10551 [17] and it is composed by three parts; in the first one the interviewed person fills information regarding age and sex, in the second one evaluations of temperature and air speed, overall thermal comfort sensation and the presence of local discomfort feelings. There is also a part in which people provide information about their dressing and, by means of this data, it is possible to estimate the corresponding thermal resistance. The last part collects information about the possibility of micro-climatic control and the satisfaction of the interviewed people about these possibilities. In this part occupants had to indicate their position on the theatre's plan (see appendix A of [15]).

By processing information acquired from the questionnaires, the following data were elaborated:

- average age of the sample and number of interviewed people;
- Predicted Mean Vote (PMV);
- Percentage of people that consider the theatre not thermally acceptable (TUI);
- Percentage of people that consider the theatre not thermally comfortable (TAI);
- Percentage of people that consider the speed of air movements not acceptable (UAMI);
- Thermal resistance of the clothing of the audience;
- Percentage of people that feels discomfort caused by too big difference between the temperature at their head height and the temperature at heir ankle height. (UVTGI).

3.2. Experimental surveys

The experimental measurements were conducted with the same methodology and instruments used formerly in previous studies [12–15]. In particular it was employed a Babuc –A storage acquisition system that fulfils the requirements of ISO 7726 [18] and that is made by LSI Lastem. Its acquisition rate can vary from 1s up to 24 h and, after downloading the data on a personal computer.

The thermal-hygrometric parameters that was detected are