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CFD Comfort Analysis of a Sustainable Solution for Church Heating

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Abstract

Historic building heating and, in particular, church heating represents a challenging task because many objectives have to be reached simultaneously, such as occupants thermal comfort and optimal internal climate suitable for the preservation of fragile building components and artworks. Moreover, current requirements for sustainability impose to make efforts, where possible, to minimize the amount of energy needed and the consequent environmental impact.

Innovative solutions are currently under research and development and are mainly based on electric radiant surfaces. The present work represents actually a detailed performance analysis of a novel hydronic high-efficiency pew-based heating system coupled with a ground-source heat pump. The system was specifically developed for the above-described application field, with particular reference to the Basilica di Collemaggio (L'Aquila, Italy), a church of worldwide relevance currently under restoration.

In detail, within the work a three-dimensional CFD analysis of the heating solution was carried out considering as application field a virtual test room containing two benches with three virtual sitting manikins. Heat exchanges between the human body surfaces, the room environment and the heated benches were simulated in order to assess the whole performance. The results show that the air temperature in the room is not significantly influenced by the heating system, but the heat is directly radiated to people, ensuring comfortable conditions and contributing to artworks preservation.

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Keywords: Friendly heating; Local comfort; Pew-based heating; Church heating; CFD.

1. Introduction

Historic building heating and, in particular, church heating represents a challenging task because different factors should be properly considered: occupants' satisfaction, conservation of historic fabric and artefacts [1-3]. In this regard, it becomes extremely important to identify the most appropriate solutions while designing the heating system of a church, provided that this should have the minimum impact on the local indoor microclimate [1]. In general, two main options have to be considered: central heating (heating the whole room) and local heating (warming people with localized heating sources) [4]. Of course, a perfect choice doesn't exist, as each system should be tailored on the features of the building. Although some research studies claim that heating the whole church's volume with efficient systems, such as heat pumps [5,6], seems to be an effective way of achieving comfort conditions [1], it can be stated that central heating represents the most invasive solution with respect to the existing historical structures and also an expensive option.

A more effective and less invasive method is based on localized comfort, by adopting heating systems able to directly provide confined heat where necessary, without dispersing too much heat inside the whole church and reducing temperature and relative humidity fluctuations (and thus the related damaging effects) in the proximity of artworks [3].

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This strategy could mainly be based on the use of radiant heaters placed on the pews, of IR lamps, of warm air emission from the floor or footboard [7-11] or else. In this respect, one of the most effective solution, both in terms of comfort and artworks preservation, is the use of electrically heated foils strategically placed on the pews to properly heat the various parts of the body [4,7,12]. However, since the Joule effect could not be considered the best option under an exergy point of view, relying on a strong energy degradation, it would be preferable to use hydronic systems, powered by high-efficiency generation systems, such as heat pumps instead of electrical radiant systems [13].

The objective of the present study is to carry out the analysis of the comfort perceived by people heated by an innovative pew developed by Politecnico di Milano, through the use of a CFD model.

The present paper represents an in-depth analysis and extension of a previous research developed by the authors [13].

2. Hydronic pew-based heating system design

In the present work, the high-efficiency hydronic pew-based heating system specifically designed for the Basilica di Collemaggio is analyzed [13]. In such system the heat transfer fluid (water) is heated by the generator, which is a water-to-water heat pump, and is distributed through small pipes to the benches and the heated footboards. The pews thus integrate hydronic radiant panels, specifically adapted for the purpose, placed in order to maximize the radiative surface and the related view factor in respect to seated peoples.

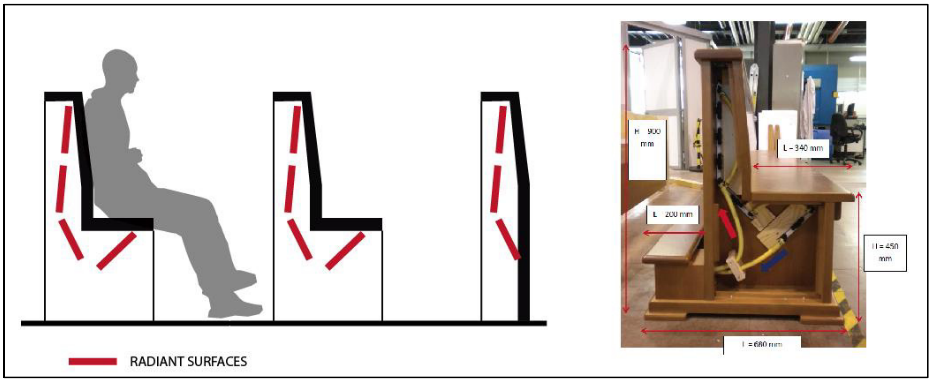

Fig. 1. Schematic of the radiant surfaces of the bench (left) and view of the realized prototype (right)

In detail, for each bench, 4 hydronic plates having dimensions equal to (L × H × W) 255 cm × 2 cm × 18 cm are used: 2 of them are coupled together and vertically placed behind the back of the bench, while the other 2 are installed under the seat, one tilted forward and the other backward, according to the scheme shown in Fig. 1. All the plates are hydraulically connected in series and the first plate at the top and the last one at the bottom of the bench are attached with the inlet and outlet copper pipes which connect each pew with the main hydraulic circuit. The wooden structure of the bench is designed to fully integrate all the pipes and the joints, and is provided with different openings in order to ensure an easy access in case of maintenance.

3. Virtual modeling and computer simulations

The comfort analysis shown in the present paper was carried out with the hypothesis to place the bench in a virtual test chamber [13], in order to facilitate the comparison with further experimental data that will be acquired in a real environmental test chamber in the prosecution of the research. In the bench, the disposition of the radiant surfaces was defined with the aim of maximizing the radiant effect and allowing the possibility for the churchgoers to see the historic floor of the Basilica. In order to verify the effectiveness of the design choices, the evaluation of parameters which affect the comfort, such as air temperature, radiant temperature and air velocity was carried out by means of a virtual model in which three manikins with real dimensions were simulated. Finally, the comfort perceived by manikins, in terms of PMV, was evaluated.

In this respect, a CFD analysis was performed with Fluent (version 16.2), which is one of the most widespread fluid dynamic software. The simulation was carried out considering 3 people seated, in order to evaluate the related thermal comfort and hence the air and the radiant temperature distributions. The simulation model was realized using Cartesian coordinates, in which an unstructured tetrahedral grid is applied. In order to reduce the computational time, only a half of the model was realized and a plane of symmetry was applied as boundary condition. It was considered reasonable because, given the physical geometry under study, the expected flow pattern and the temperature distribution are symmetrical considering the middle plane SP as shown in Fig. 2.

Within this CFD model, in the numerical solution, a second Order Upwind discretization method was used for convection terms, the SIMPLE algorithm was chosen for pressure-velocity coupling and the Discrete Ordinates radiation model was used to take into account the radiation exchange between surfaces. Turbulent flow model was considered in the k–α model with standard wall functions.

The validity of such model in the indoor environment analysis was proven accurate [14].

Because no forced ventilation is expected, while heat is supplied by radiation and natural convection from the heating elements, the Boussinesq approximation was used for the air density. The radiant plates and the wooden structure of the bench were modelled as a whole object, characterized by different surface temperatures according to the first experimental measurements carried out in the environmental test chamber and shown in the previous research [9]. The wall boundary conditions as well as ceiling and floor temperature were set to 10 °C, according to the mean temperatures expected inside the church during winter period. Moreover, it was assumed that the temperature of the manikins' surfaces without clothes (e.g the head.) was constant and equal to 33.7°C with an emissivity of 0.95, while the surfaces covered by clothes was set to 33 °C with an emissivity of 0.85 [14].

Furthermore, considering that the COP (Coefficient of Performance) of a water-to-water heat pump is decreasing with the increasing of the temperature difference between the heat source and the heated water, according to an exponential function related with the Carnot efficiency, it is better to minimize the supply water temperature of the system to obtain the maximum energy performance and also to reduce the thermal losses of the distribution pipes. In this sense, according to the results of previous research, the optimal value of the supply water temperature of the bench was set equal to 35 °C [13].

Finally an emissivity of 0.94 for the bench was considered; such value was defined through experimental measurements by comparing the temperature measured by an IR camera and the temperature measured by surface sensors.

Fig. 3 and 4 show the main results after one hour of system's operation for air temperature and radiant temperature distribution in the main section of the environmental chamber.

The simulation results show that the vertical increase in air temperature along the room is of about 2.7 °C and thus it does not cause abrupt or substantial changes which could damage the artefact in real applications. In fact, as already said, the main advantage of the local heating system is that the air in the building is not heated towards high temperatures, but that the heat is directly radiated to people.

Whereas the air temperature around the benches rises slightly (with a temperature of about 14.5 °C), the radiant temperature at the positions where the people are seated reaches an average level of 22 °C or higher.

Such values can be considered suitable for providing human thermal comfort especially considering the manikin seated in the middle where values of radiant temperature are achieved higher than 22 °C.

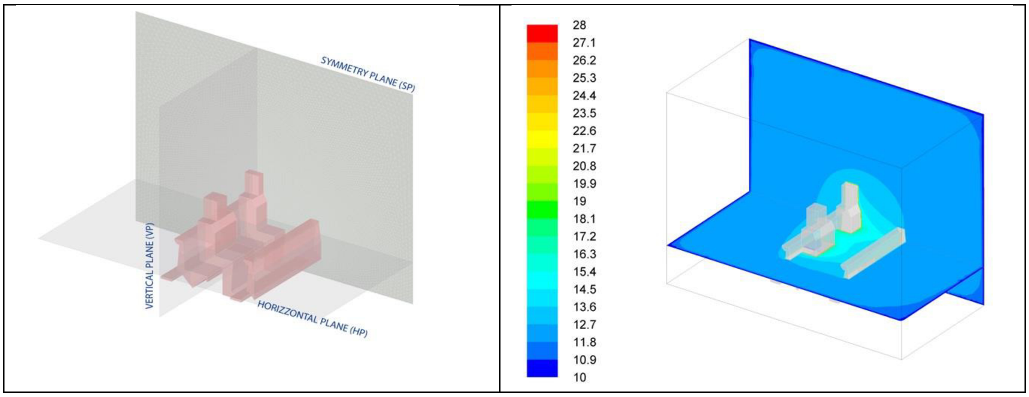

Fig. 2. Section key planes (left) and air temperature distribution on the symmetry and horizontal planes (right)

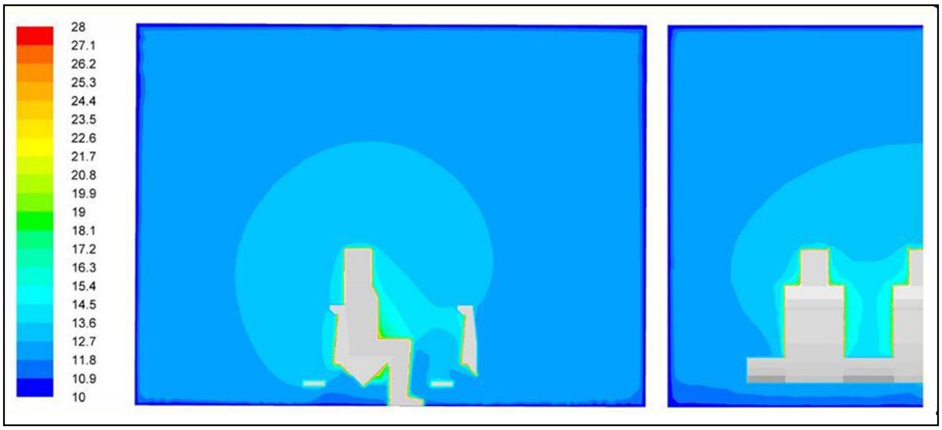

Fig. 3. Air temperature distribution on plane SP and VP

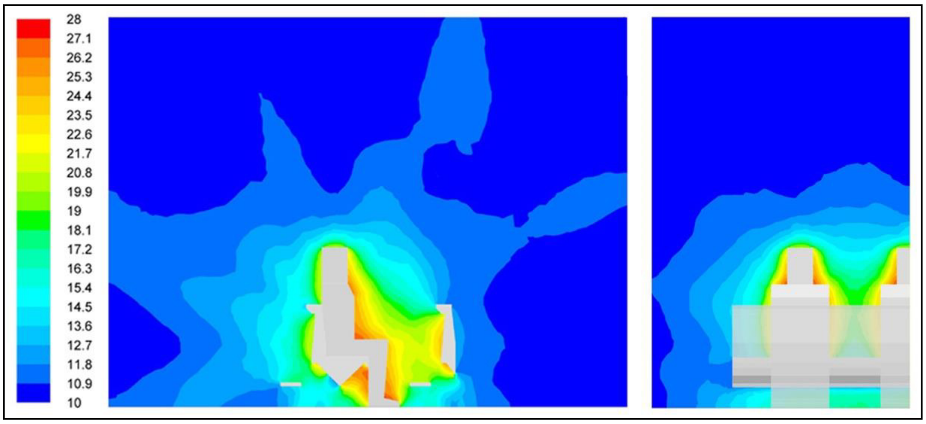

Fig. 4. Radiant temperature distribution on vertical plane SP and VP

It should be noted that the radiant temperature calculation consists of the determination of view factors in every point of the room where comfort is to be calculated. It is based on the geometric position of the irradiated surface (human body) surrounded by surfaces with different temperatures. Such value is calculated in relation to the human body surface area and orientation. The larger is radiant surfaces area and the closer is the person to them, the more is the influence of surface temperatures on people. The radiant temperature, thus, changes with the position in the room.

4. PMV calculations

By considering the human body as whole, the predicted mean vote (PMV) can be used to estimate the thermal comfort conditions of the virtual churchgoers.

The PMV is an index that predicts the mean value of the votes on the thermal sensation scale by a large group of people. Such index, which can be evaluated according the ISO 7730, takes into account all environmental factors (temperature, speed and humidity of air, radiant temperature), the activity being carried out by the person, and clothing insulation [15].

Zero is the ideal value, representing thermal neutrality, and the comfort zone is defined by the combinations of the six parameters (air temperature, radiant temperature, relative humidity, wind velocity, clothing and metabolic activity) for which the PMV is within the recommended limits ($-0.5<PMV<+0.5$) [16].

In the present work, the PMV was evaluated considering a metabolic rate typical of a seated person (0.9 met) and with a clothing insulation equal to 2.1 clo, which corresponds to winter cloths with overcoat (open at front part around the chest, as is likely for a person coming from outside and sitting in the hypothetical church).

The wind speed was set at an average value of 0.08 m/s according to the simulation results shown in Fig. 5 (left).

Finally, in Fig. 5 (right) the PMV calculated considering a relative humidity of 30% and 70% (which is respectively the typical minimum and maximum relative humidity of the expected application context) is reported. The value is respectively equal to -0.3 and -0.1, which, according to the standard EN 15251 [17], can be defined a state of neutrality confirming that the comfort condition is reached.

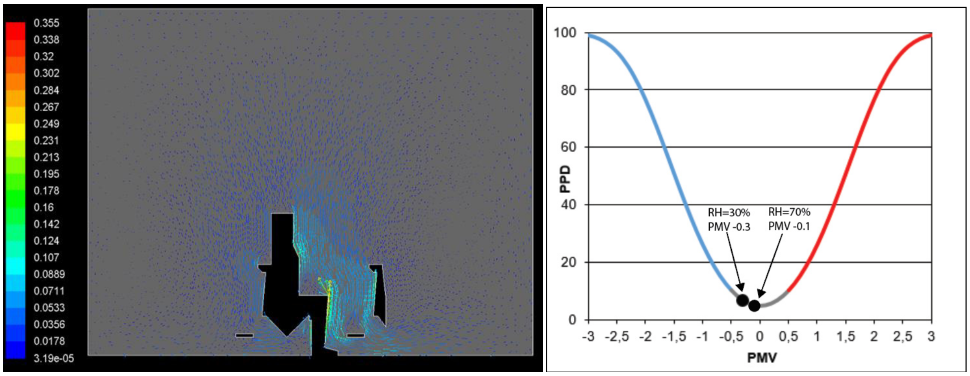

Fig. 5. Velocity distribution, in m/s, on plane SP (left) and PMV diagram (right)

5. Conclusion

In this study, the performance of an innovative local heating solution was analyzed in terms of thermal comfort. The proposed system was numerically simulated by using a three-dimension computational fluid dynamic model. The distribution of air temperature, radiant temperature and wind velocity were used to estimate the effects on the human thermal comfort. The work allowed to confirm that pew-based friendly heating is an effective solution for historic churches as it provides good local comfort levels, ensuring at the same timelow or no impact on the art-works and on the building structures. In addition, it was demonstrated that the proposed hydronic solution is able to effectively combine the advantages of radiant benches with those of water-to-water ground-source heat pumps.

6. Copyright

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Biography

Fabrizio Leonforte is a research fellow at Department of Architecture, Built environment and Construction engineering. He has carried out different theoretical and experimental works on renewable energy and energy efficiency in buildings. He has been also involved as advisor in national and international researches as well as in different project with NGOs and Universities for capacity building of local staff.