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Microclimate Investigation in a Conference Room with Thermal Stratification: An Investigation of Different Air Conditioning Systems

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Abstract: This paper investigates the microclimate in a conference room with thermal stratification, taking as a case study the chapel of Villa San Saverio, now the seat of the "Scuola Superiore" of the University of Catania (Italy). Surveys of the former chapel were conducted to monitor air temperature and relative humidity. Subsequently, the investigation relied on numerical simulations of a simplified computational fluid dynamics (CFD) model built with the DesignBuilder v7.0 software and validated by comparison with measured values. Simulations were then carried out considering three different scenarios: the current state without any HVAC system and two possible HVAC system configurations providing both air conditioning and ventilation. The results show that, from a comfort perspective, a lightweight radiant floor heating system, assisted by an appropriate ventilation system for air renewal placed at the floor level near the occupants, is preferable to floor-level fan coils and high ventilation channels. Furthermore, this was also confirmed by a preliminary energy analysis of the two HVAC options, where the ventilation effectiveness of the winter period, the temperature of the water the emitters are fed, the consequent COP value of the heat pump, and the electricity consumption were taken into consideration.

Keywords: thermal comfort; thermal stratification; historic building; radiant floor; ventilation

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1. Introduction

The issue of reducing energy consumption in buildings is extremely urgent and current, considering that they are responsible for 36% of greenhouse gas (GHG) emissions and 40% of final energy consumption in Europe [1–3]. This challenge is particularly relevant in the context of historical buildings, which often face significant limitations in terms of energy efficiency improvement due to their cultural and architectural value [4].

Among heritage buildings, churches play a significant socio-cultural role in Europe because they are historical buildings that host large numbers of people for brief religious rites with long intervals in between when these premises are almost unoccupied. In such buildings, indoor microclimate conditions (i.e., air temperature, relative humidity, and air velocity) are determined primarily by the outdoor weather conditions, building structure, and size [5].

Because the high humidity and low temperatures found in most churches are detrimental for the occupants' comfort, solutions aimed at providing space heating began to spread in between the nineteenth and the twentieth centuries. In fact, these buildings were not originally designed or built for any mechanical system provision. Such mechanical systems were then installed to temporarily improve occupants' thermal comfort [6–8], and the heating systems most commonly installed were forced-air and hot-water radiators because of their low initial costs and the quickness with which they can heat the air inside churches. However, the thermal stratification in buildings with large volumes, such as churches, emerges as a critical issue [9–12]. These spaces, characterized by high ceilings, can present unique challenges in terms of heat distribution and thermal comfort. The existing literature highlights how traditional heating systems may not be adequate for these environments, often leading to excessive energy consumption and uneven heat distribution [13–17]. For example, Maroy et al. [15] examined energy use and the indoor climate in a medieval church, highlighting how heating systems can negatively impact occupants' comfort. Furthermore, Muñoz-González et al. [14] discussed the use of passive environmental techniques and air conditioning systems in historical churches, proposing a method to assess thermal comfort before intervention.

Research on optimizing HVAC systems in such buildings is therefore of fundamental importance, also in light of the ongoing climate change, which is one of the most critical global challenges of our time. Indeed, climate change affects indoor comfort conditions, which is even more problematic for historical buildings where discomfort is already experienced in most cases as highlighted above. The current literature includes very few studies on the effects of climate change on the environmental conditioning of historical buildings [18], and most of these studies are linked to the consequences of increased rainfall and rising sea levels and mainly analyze the damage caused to heritage buildings, especially in northern European countries.

However, the expected increase in air temperature poses serious concern also in terms of people's thermal comfort in the summer, an aspect that has been almost ignored in the current literature as demonstrated by the very few studies dealing with space cooling in churches [19]. Research by Semprini et al. [20] on an ancient, repurposed church highlights the importance of integrated solutions for thermal comfort, a concept that is also central to our study. The use of Computational Fluid Dynamics (CFD) simulations, as discussed by Akkurt et al. [21] and Huerto-Cardenas et al. [22], provides a detailed understanding of internal thermal conditions in large-volume spaces. These tools are essential for informing design decisions and ensuring that the proposed solutions are both effective and respectful of the building's historical heritage.

In order to advance the knowledge of indoor microclimate conditions in churches, this research takes the chapel of Villa San Saverio, now the headquarters of the "Scuola Superiore" of the University of Catania, as a case study to explore innovative and sustainable HVAC solutions for heating and cooling. In this article, we examine two different configurations of the HVAC systems that can ensure both thermal comfort and effective ventilation for the occupants, namely a fully convective system (fan–coil units plus primary air distribution ducts) and a radiant floor system including floor-level inlet vents for the primary air inlet. The CFD simulations show that, if properly sized to meet the cooling loads, the two solutions allow the same degree of thermal comfort, measured by the Predicted Mean Vote; however, the second solution, placed entirely at the floor level, allows a more effective ventilation in the occupied space, while also avoiding the installation of unesthetic air distribution ducts that are not easy to conceal in a repurposed church. The paper also shows that the use of a radiant floor solution in historic buildings with large volumes avoids the unnecessary heating of the air in the upper layers [23] and ensures around 20% energy savings, also thanks to the higher average performance of the heat pump and the absence of fans in the terminal units.

2. Materials and Methods

This study investigates the microclimate conditions of a conference room in a historical building, specifically the chapel at Villa San Saverio, owned by the University of Catania. The methodology involved the stages summarized in the flowchart of Figure 1.

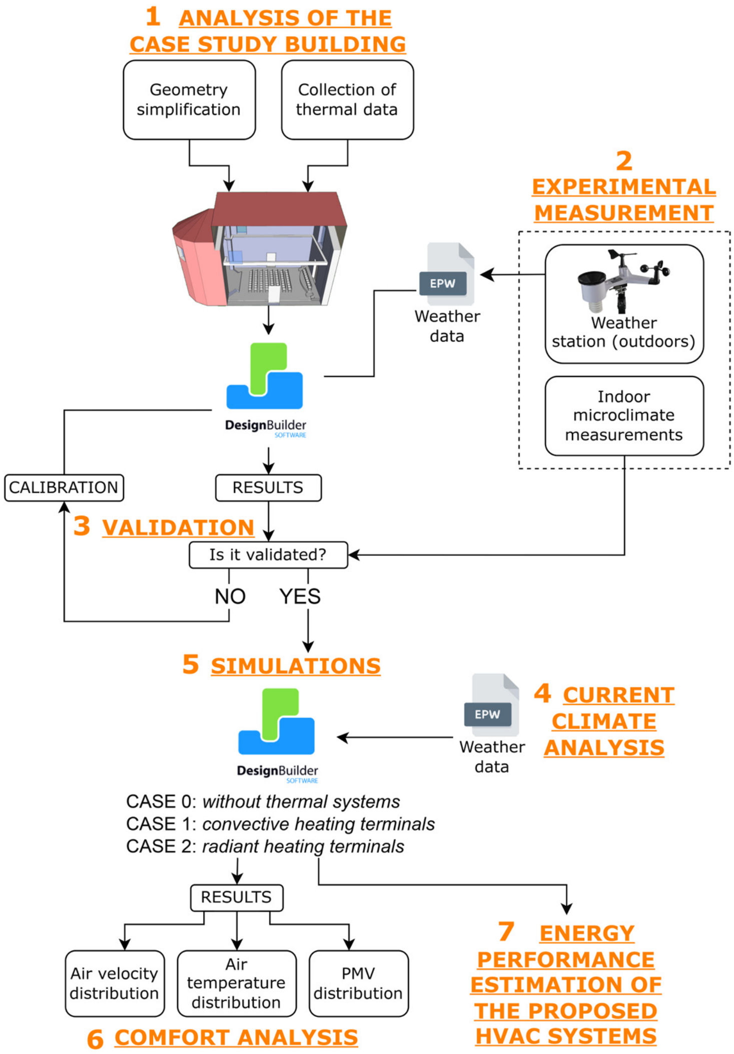

Figure 1. Workflow of the methodology.

The initial phase (phase 1) of our study required a detailed analysis of the case study building. This involved simplifying the building's geometry and constructing a virtual model using DesignBuilder software. In this phase, the data on the thermal features to be assigned to the virtual model of the building were collected by examining buildings from other studies in the same geographic area and construction period.

The subsequent step (phase 2) involved carrying out preliminary experimental measurements, which were instrumental for the validation of the virtual model in phase 3. Data on the chapel's internal environment, including air temperature and humidity, were gathered over four days in March 2022 using specific instruments like Wöhler CDL 210 dataloggers and a TESTO 435 heat flow meter. These were placed at various heights to obtain an informative vertical thermal profile. Additionally, this step required the collection of meteorological data to be included in the weather file, which was then utilized for the validation simulations. The validation was based on the calculation of different error indices for air temperature only [24], whose suggested thresholds according to Huerto-Cardenas et al. [22] are indicated in Table 1: MBE (Mean Bias Error), MAE (Mean Absolute Error), RMSE (Root Mean Square Error), r (Pearson's Correlation Coefficient), and R^2 (Coefficient of Determination).

Table 1. Suggested thresholds for error indices [22].

	MAE	RMSE	r	R^2
LV 1	≤1 [°C]		>0.5	>0.75
LV 2	≤2 [°C]			

Once the model was validated, we proceeded to phase 4, analyzing the current climate by using the typical meteorological file of the city of Catania developed by some of the authors [25]. This analysis was essential to understand the environmental context of the building.

In phase 5, the study then simulated three different HVAC system configurations under winter and summer conditions, examining (in phase 6) air temperature distribution, air velocity, and thermal comfort, measured by the Predicted Mean Vote index.

Finally, in phase 7, the study compared the energy performance of the proposed HVAC systems by assessing their electricity consumption, heat pump efficiency (COP), and overall effectiveness in both the heating and the cooling seasons.

2.1. The Building Case Study and the Monitoring Campaign

The building case study is part of the Villa San Saverio, the current seat of the "Scuola Superiore" of Catania, Italy. This is a higher education center of the University of Catania, which was founded in 1998 with the aim of selecting the best young students and offering them a course of study that includes both research and experimentation [26].

Villa San Saverio is a building with a large internal courtyard and rich decorative elements (see Figure 2a,b) that make it a place of cultural interest (the plan and longitudinal section are shown in Figure 3). It was built in 1880, and for the first two decades, it was intended for residential use. Later, after being the seat of the "Istituto Agrario Siciliano Valdisavoia" of the "Collegio San Luigi di Birchircara di Malta" and of the Jesuit Community [27], in 2001, its history intertwined with the University of Catania [28].

Figure 2. Façade (**a**) and interior view illustrating the verticality of the space (**b**) of the former chapel.

Coming to the chapel, the net height at the keystone of the barrel vault is about 10.80 m. The floor, also including the apse, has a net floor area of about 125 m^2 and is oriented with the long side (about 18 m long) to the north. The total net width is about 7.50 m, and the radius of the apse is about 3.70 m. The north and south façades face outdoors, while the other two façades partially border with other parts of the building complex. The walls have a thickness of 0.80 m and are made with irregular lava stones. The roof is vaulted (barrel type) and is made of a pumice and plaster conglomerate with an overlying wooden gable roof and tile roof. The main entrance is an external door with two solid wood panels of 2.00 m × 3.70 m; there are also two secondary entrances of 1.50 m × 2.95 m, placed in the middle of the two longitudinal sides. In the clerestory, above the cornice that is located at a height of 6.55 m, there are six windows: three are in the apse area, one is above the entrance door, and the other two are on the two longitudinal walls. The window on the south façade measures 2.30 m × 3.20 m, while the others have dimensions of 1.50 m × 1.80 m.

In order to validate the model that was subsequently built on the dynamic energy simulation software DesignBuilder, thermo-hygrometric measurements were carried out from 4th to 7th March 2022. This period was selected because of the renovation work that was going to start in the next days and would have made taking any experimental measurements unfeasible for some months. Despite the short period of time to perform measurements, the experimental activity returned interesting information thanks to the careful selection of the probes' positions. This approach was inspired by the methodology outlined in [29], where Costanzo et al. demonstrated that significant insights into the microclimatic risks and conservation issues within heritage buildings could be obtained not necessarily through extended monitoring, but rather through the strategic placement of sensors in order to capture the key physical phenomena. Following this precedent, our study also employed a targeted monitoring strategy, selecting specific days for data collection and positioning probes at the centerline of the nave (longitudinal direction) and at different heights. More specifically, two types of instruments were used to measure the air temperature. First, two Wöhler CDL 210 dataloggers (Figure 4) were positioned at 4 m and 6 m from the floor (they are indicated with the letters B and C in Figure 3b, and their technical features are listed in Table 2). Then, a TESTO 435 heat flow meter (Figure 5) equipped with a radio probe for measuring the air temperature only was positioned at a height of 1 m from the floor (indicated with the letter A in Figure 3b; the technical features are reported in Table 3).

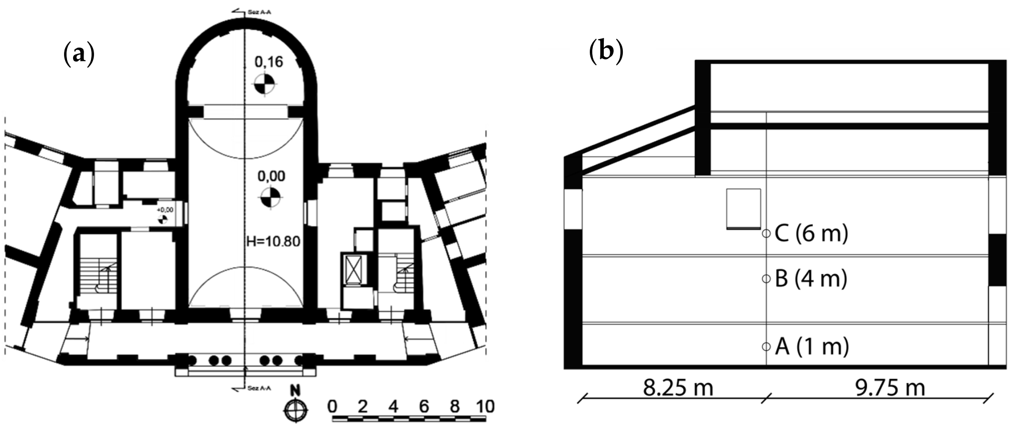

Figure 3. Plan view (**a**) and longitudinal section (**b**) of the former chapel with indication of the instruments' locations.

Figure 4. Wöhler CDL 210 datalogger.

Figure 5. TESTO 435 heat flow meter.

Table 2. Technical features of Wöhler CDL 210 datalogger.

	Temperature	Relative Humidity
Measuring Range	from −10 °C to 60 °C	5% to 95%
Resolution	0.1 °C	0.1%
Accuracy	±0.6 °C	±3% for 10% and 90%, ±5% otherwise

Table 3. Technical features of the TESTO 435 datalogger.

	Temperature
Measuring Range	from −50 °C to 100 °C
Resolution	0.1 °C
Accuracy	±0.2 °C when −25 °C < T < 74.9 °C ±0.4 °C when −50 °C < T < −25.1 °C ±0.4 °C when 75 °C < T < 99.9 °C ±0.5% for all other values

2.2. CFD Modeling and Simulation Scenarios

The 3D model was created in the DesignBuilder software tool, which allows for the performance of both thermal and CFD simulations. DesignBuilder is an intuitive modeling environment where the user can draw the building model in 3D and assign various thermal and physical features (e.g., materials, thermal loads, and technical systems) [30].

A simplified three-dimensional model was built to carry out the necessary simulations: in particular, the apse was rectified, the apsidal basin was approximated to 3 pitches, the triumphal arch was not considered, and the difference in height (17 cm) between the nave and the apse areas was not modeled either. The simplifications were made considering that, for the purpose of this analysis [31,32], it is particularly important to know the vertical distribution of air temperature, especially in the areas of the chapel used by the public. For this reason, specific care was taken with respect to modeling the vertical development of the building, so the highest point of the nave (about 10.80 m from the floor) was retained as measured in situ.

Based on this rectified and simplified geometry, a non-uniform rectilinear Cartesian grid with a spacing of 0.30 m was implemented. The non-uniform grid means that the grid lines are parallel with the major axes and the spacing between the grid lines enables non-uniformity; i.e., the 0.30 m spacing can be made finer when in presence of obstacles (i.e., fan coils, people, and furniture) and then restored for the remaining domain. In order to avoid the creation of cells with a high aspect ratio that can lead to instability in the solver of the Navier–Stokes equations, the temperature equation, and the k-e turbulence model, a grid merge tolerance of 0.025 m was used, meaning that cells with smaller dimensions were automatically merged.

Internal boundary conditions were defined by assigning the following specific conditions:

- Walls and windows as fixed surface temperatures of 23 °C and 12 °C, respectively. These values were set according to the results of preliminary dynamic thermal simulations in DesignBuilder run for the investigated days.
- People are objects releasing a sensible heat flux of 100 W each.
- Supply and extract air diffusers via their flow rates, air temperatures, and azimuthal/zenithal discharge angles. The specification of such values is presented in the description of the simulation cases afterward.

As for the thermal features of the opaque and transparent envelopes, they were gathered from other studies concerning the same geographical area and construction period [33–35]: the uninsulated external walls (green surfaces in Figure 6) have U = 1.56 W/(m^2 K), while for the pitched roof (yellow surface in Figure 6), U = 1.14 W/(m^2 K). The ground floor (dark grey in Figure 6) shows U = 1.46 W/(m^2 K); the wooden door has U = 0.90 W/(m^2 K); the double glazing of the openings was assigned U = 2.70 W/(m^2 K), while their wooden frame has U = 3.63 W/(m^2 K).

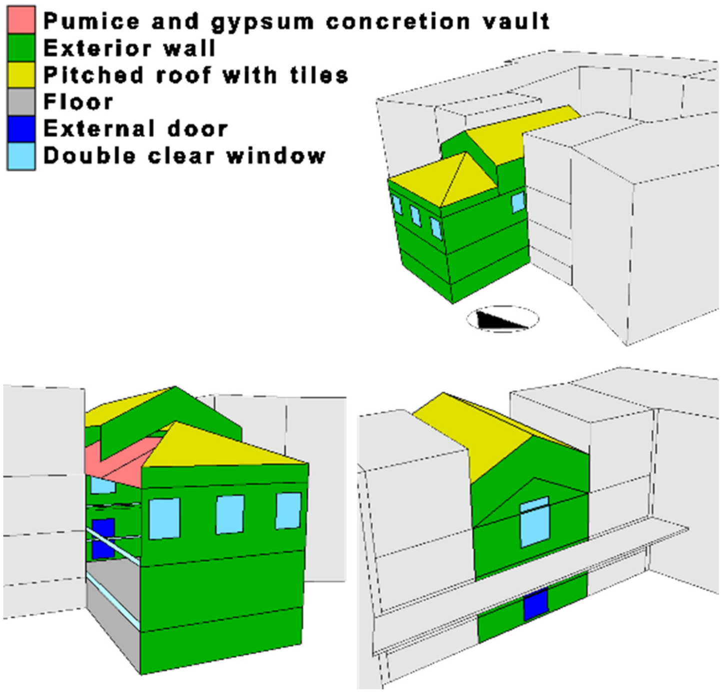

Figure 6. Three-dimensional model of the former chapel with different construction assemblies highlighted with different colors.

Then, after the validation phase (the results of which are described in the first paragraph of Section 3), three different scenarios were developed for the sake of comparing the comfort conditions achievable with different suitable HVAC systems. The first scenario, called "Case 0", is the current state without any HVAC systems. The second one, called "Case 1", includes an HVAC system consisting of floor-level fan coils for heating/cooling purposes plus two perforated ventilation channels providing outdoor fresh air, placed at h = 6.55 m above the floor along the two sides of the chapel (Figure 7). The third configuration, called "Case 2", consists of a dry radiant floor system for radiant heating/cooling purposes, plus eight vents for an air inlet placed at the level of the floating floor with a size of 2 × 0.2 m (Figure 8).

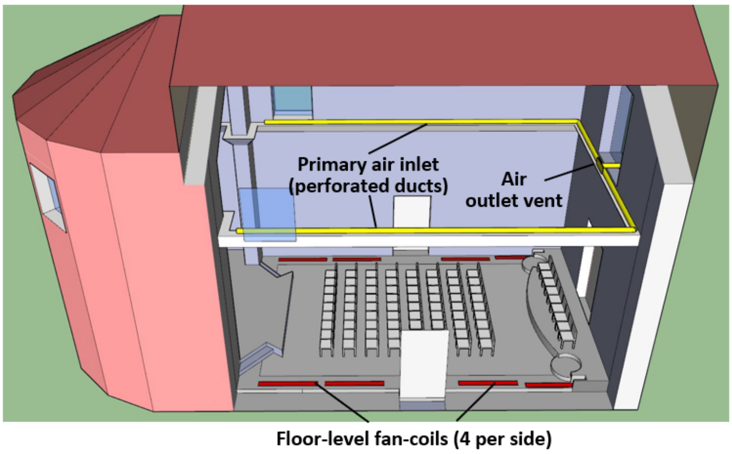

Figure 7. Position of the HVAC systems ("Case 1").

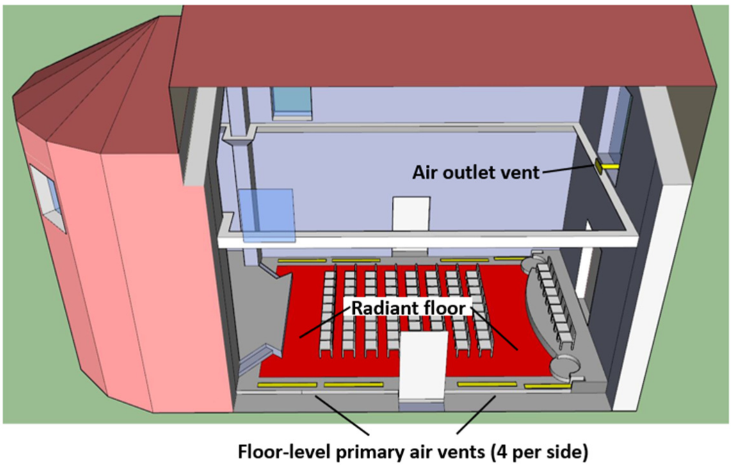

Figure 8. Position of the HVAC systems ("Case 2").

Coming to the sizing of the HVAC systems, this was focused on meeting the design cooling loads, which are far higher than heating loads in crowded indoor environments such as churches, theaters, and conference rooms. The sensible cooling load in the summer was calculated by adding up the various contributions: the sensible thermal load from people in the room (80 people × 100 W each, totaling 8 kW), artificial lighting (24 lamps × 165 W each × 0.7 convective ratio, totaling about 2.7 kW), electrical equipment estimated at about 500 W, and transmission load through the envelope amounting to 800 W with an outdoor design temperature of 36 °C. The sum of these contributions provides a total sensible cooling load of approximately 12.0 kW. Latent loads (and the inlet humidity of the primary air) are not relevant for this study.

The HVAC system must also provide air renewal through controlled mechanical ventilation. To this aim, a minimum air flow rate of 20 m^3/h per person was considered, as stated by the National Standard UNI 10339 [36] in the case of theatres and conference rooms. Because the chapel is designed to host 80 people, this corresponds to at least 1600 m^3/h; however, the design flow rate was increased to 2000 m^3/h so that the ventilation flow rate can also provide a significant contribution to the heat load management.

In "Case 1", the eight fan coils are located along the perimeter of the floor area and work with an air flow rate of 500 m^3/h each; air is released at 25 °C in the winter and 20 °C in the summer, and in both cases, the air flow is emitted upward through grilles with a design supply air velocity of 0.35 m/s. On the other hand, as explained above, the ventilation channels (350 mm diameter, which corresponds to a velocity of 3 m/s) release an overall air flow rate of 2000 m^3/h at a temperature of about 20 °C both in the winter and in the summer, through 20 mm nozzles distributed along the channel side. Indeed, in the winter, the selected fan coils are already able to meet the heating load; thus, the primary air has only ventilation purposes, and its inlet temperature is the same as the indoor air (20 °C).

In "Case 2", the dry radiant floor has a surface temperature of 26 °C in the winter and 20 °C in the summer; in cooling operation, this corresponds to 40 W/m^2 of sensible cooling effect, which is not possible to overcome if uncomfortably low floor temperatures must be avoided. Each floor-level air vent introduces an air flow rate of 250 m^3/h at a temperature of 20 °C in the winter and 15 °C in the summer with a purely upward flow (design supply air velocity of 0.2 m/s). Here, again, the primary air contributes to meeting the heat loads only in the summer; the difference between the summer inlet temperature of the primary air assumed in "Case 1" and "Case 2" is due to the limited heating and cooling capacity of the radiant floor, which calls for a further contribution to the sensible load by the primary air, whose inlet temperature is now 11 °C below the indoor set point temperature in the summer. Lower inlet temperatures are not suitable to avoid local thermal discomfort due to cold air draughts.

For the different simulation scenarios, in addition to air temperature and air velocity calculations in the occupied space, indoor thermal comfort conditions were also assessed by determining the spatial distribution of the Predicted Mean Vote (PMV) index. Such an index was developed by Fanger based on several experimental studies conducted in the laboratory considering the main variables that affect human thermal sensation: air temperature, mean radiant temperature, air velocity, relative humidity, metabolic activity, and thermal resistance of clothing [37].

The simulations for the calculation of comfort conditions were finally carried out considering an indoor relative humidity of 55% and a metabolic activity for the occupants equal to 1 met (sedentary activity). Regarding the clothing index, 1 clo was assigned for a typical winter day (23 December) and 0.5 clo for a typical summer day (1 July).

3. Results and Discussion

3.1. Validation of the CFD Model

To validate the CFD model, simulations were carried out using the weather conditions measured from 4 to 7 March 2022 at the weather station owned by the local agrometeorological service SIAS [38]. Figure 9 shows the outdoor air temperature and the horizontal solar irradiance on the selected days.

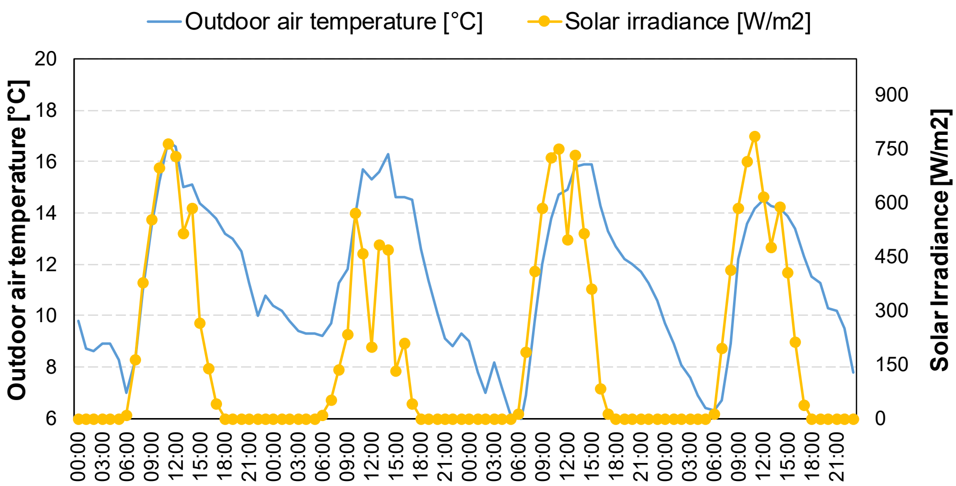

Figure 9. Outdoor air temperature and solar irradiance from 4 to 7 March 2022.

Then, Figures 10 and 11 report the air temperature distribution provided by the CFD simulations (at 14:00 on 6 March) and the measured temperatures at the different heights, respectively, where the probes were positioned during the monitoring campaign. The numerical values reported in the table inside Figure 11 demonstrate that the thermal stratification, i.e., the difference between temperature values at 6 m and at 1 m, ranges between 0.2 °C and 1 °C. The difference between the measured and simulated values is low; only 4 out of 24 temperature measurements (about 16.7% of the total) differ by approximately ±1 °C, while 17 of these (70.8% of the total) differ by less than ±0.50 °C. Indeed, half of the total measurements deviate from the corresponding simulations by less than ±0.2 °C. Furthermore, Figure 11 shows that the variations are more relevant in the early hours of the day, at 6 a.m., while during the remaining part of the day, the model shows very good agreement with the measured values. In addition, the most important variations occur at a height of 4 m and 6 m, while at a height of 1 m, near the people, there is an excellent match. To further validate the accuracy of the CFD model, the average coefficient of determination is R^2 = 94%, the average Pearson's correlation coefficient is r = 98%, the average Mean Absolute Error (MAE) is 0.37 °C, and the average Root Mean Square Error (RMSE) is 0.47 °C. These figures confirm that the model built in DesignBuilder can be considered validated.

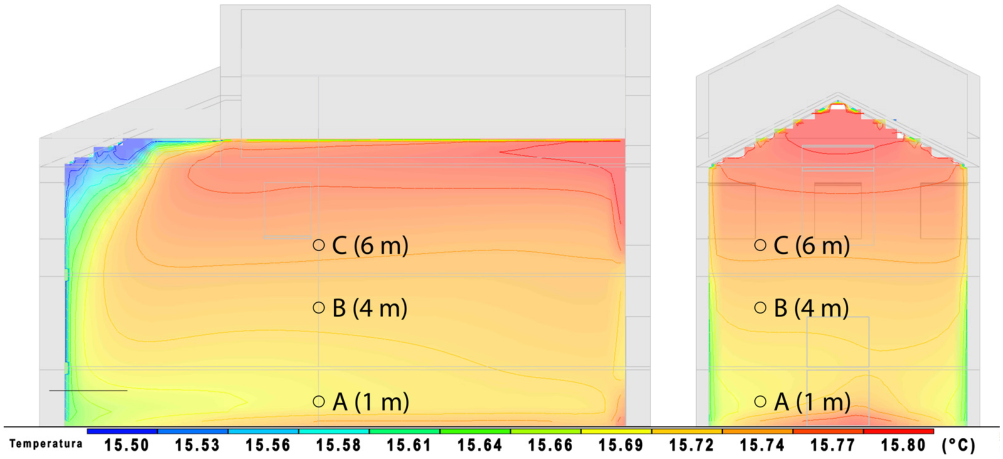

Figure 10. CFD simulation results at 14:00 on 6 March.

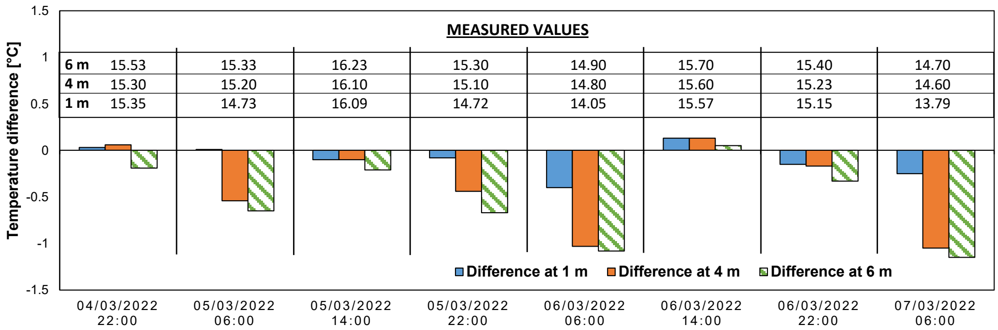

Figure 11. Difference between simulated and measured temperatures at different heights.

3.2. Air Velocity Distribution

The results described hereafter and in the next subsections refer to a day of a typical winter week (23 December) and a day of a typical summer week (1 July) at 21:00. The choice of these specific days was made after a statistical analysis of the long-term local climate data, while this time was chosen because museum exhibitions or evening theatre performances usually take place at this time.

During the winter day, Figure 12 suggests that in "Case 0", the air velocity near the occupants is about 0.15 m/s, while it is about 0.10 m/s in "Case 1" and 0.15 m/s in "Case 2". Furthermore, it can be noted that in "Case 1", the fresh air does not have a strong tendency to move toward the occupants, while in "Case 2", the ventilation is more effective as the fresh air easily reaches all the occupants.

On the typical summer day in "Case 0", the air velocity near the occupants is about 0.05 m/s, in "Case 1" it is about 0.15 m/s, while in "Case 2", it is about 0.10 m/s. Furthermore, both "Case 1" and "Case 2" show an effective ventilation pattern: in fact, in summer, the fresh air of "Case 1" tends to move toward the occupants, because cold air has a higher density than hot air.

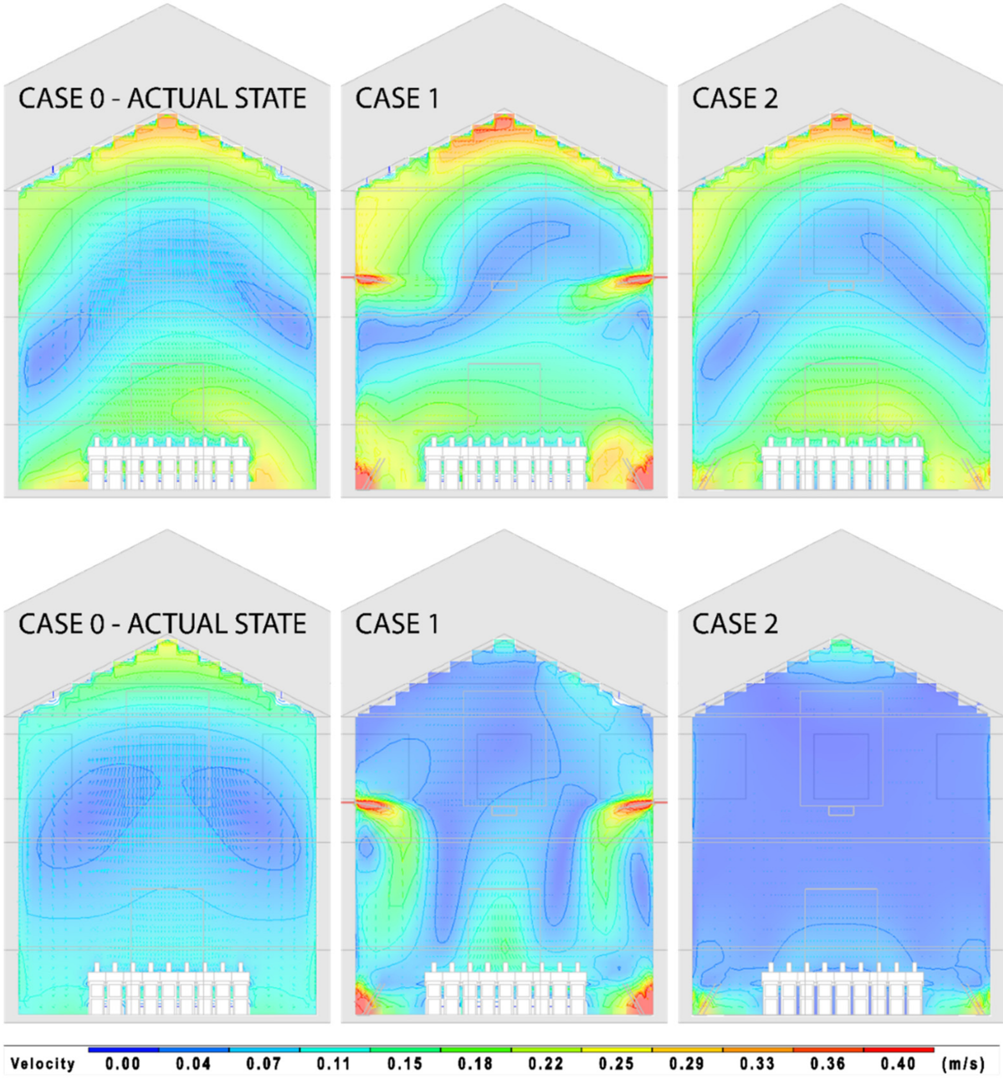

Figure 12. Air velocity distribution on 23 December (first row) and 1 July (second row) at 21:00.

3.3. Air Temperature Distribution

Figures 13 and 14 show the air temperature distribution at 21:00 of the typical winter day (Figure 13) and of the typical summer day (Figure 14). The figures refer to two cross-sections, cut in the middle of the zone occupied by the audience. The reported numerical values refer to a vertical line placed 50 cm ahead of the first row of occupants; however, comments will also refer to the temperature distribution inside and above the occupied zone.

Considering a typical winter day (Figure 13), in "Case 0", the air temperature is 17.7 °C in the lower part of the former chapel and 18.1 °C in the upper part, with limited thermal stratification. Moreover, the air temperature is around 19.0 °C near the occupants. In "Case 1", it is 19.9 °C in the lower part of the indoor environment and 20.6 °C in the upper part, while it is about 22.3 °C near the occupants. On the other hand, in "Case 2", the air temperature is 19.4 °C in the lower part and 20.0 °C in the upper part, while it is 21.5 °C near the occupants.

Thus, one can observe that the use of a convective terminal (Case 1) implies higher temperatures in the occupied zone, i.e., around 1 °C more than with a radiant floor (Case 2). Furthermore, in “Case 1”, the air in the upper part of the chapel is warmer (20.6 °C) than the air in “Case 2” (20.0 °C). This is a further demonstration that the convective heating system affects the entire air volume, thus overheating the top air layers and, basically, wasting energy, unlike the radiant system. However, although in both cases the presence of many people triggers the heating of the air and consequently the thermal stratification process, it is evident that in “Case 2”, this effect is noticeably reduced.

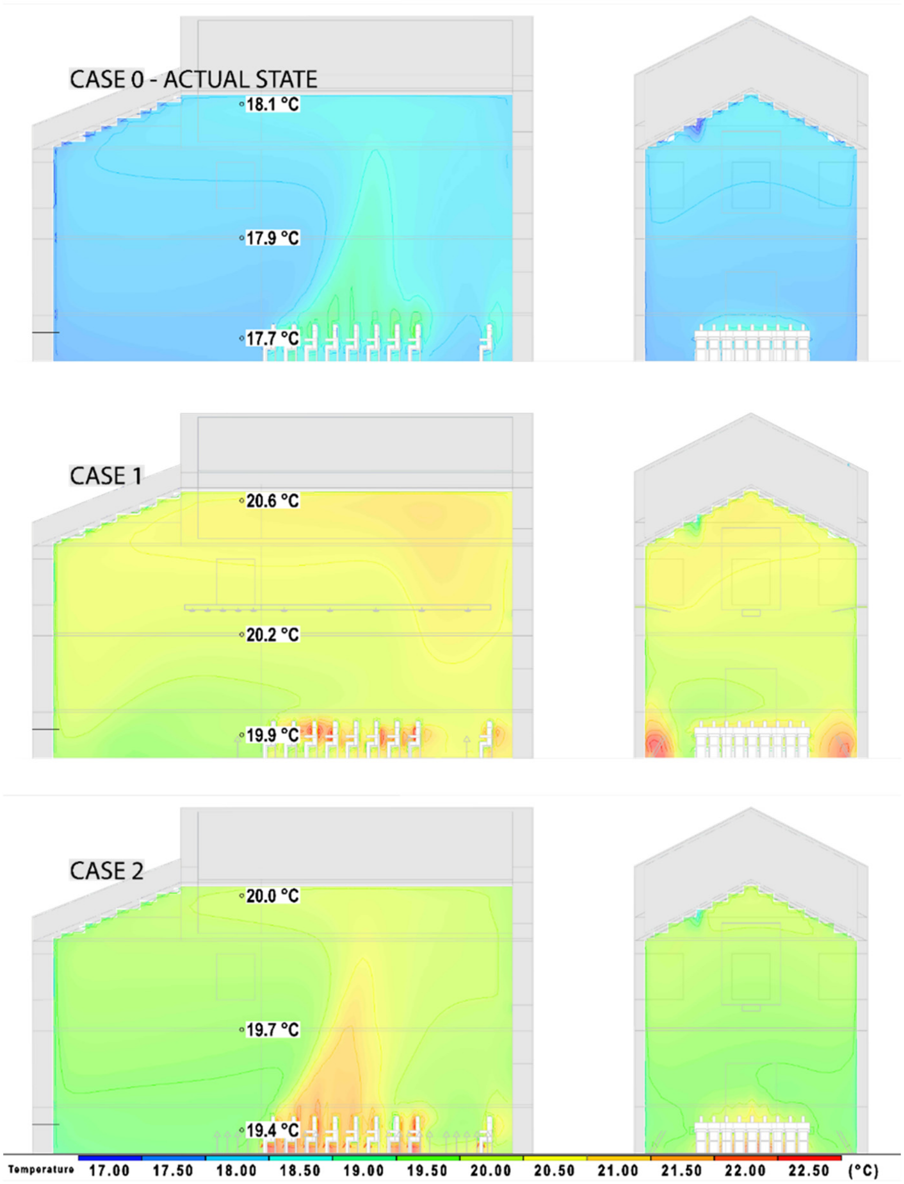

Figure 13. Air temperature distribution on a typical winter day (23 December at 21:00).

On the typical summer day (Figure 14) in “Case 0”, the air temperature is 28.0 °C in the lower part and 28.5 °C in the upper part. The air temperature is around 29.0 °C near the occupants, suggesting a non-negligible space overheating and possible discomfort. In “Case 1”, the air temperature is 23.8 °C in the lower part and 26.5 °C in the upper part, while it is around 26.5 °C near the occupants. On the other hand, in “Case 2”, the air temperature is 24.2 °C in the lower part and 26.7 °C in the upper part, while it is 25.9 °C near the occupants. Furthermore, it can be noticed that in "Case 1", even the air in the upper part of the chapel is partially cooled, although this is not needed for comfort purposes, while in "Case 2", the air in the top layers remains slightly warmer and thermal stratification is slightly less pronounced.

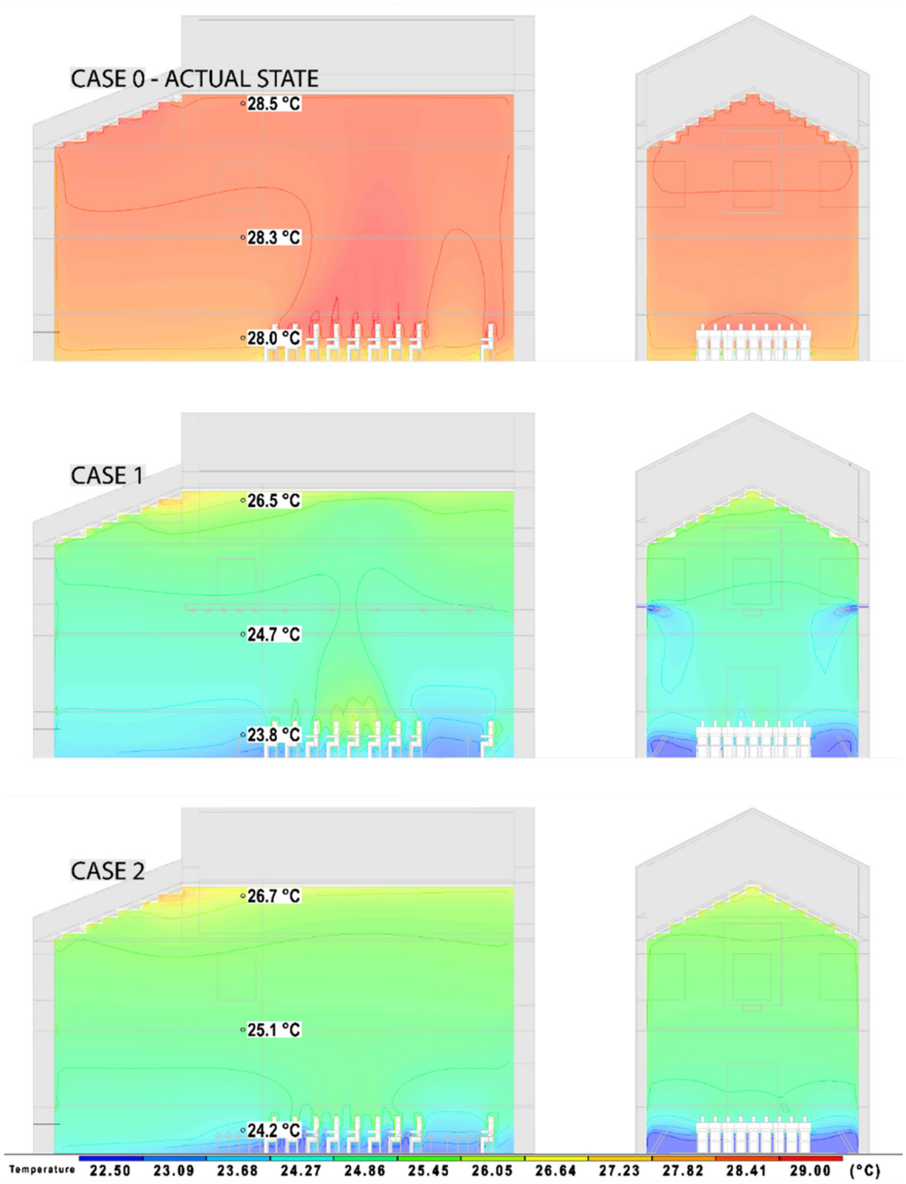

Figure 14. Air temperature distribution on a typical summer day (1 July at 21:00).

3.4. PMV Distribution

Figure 15 shows the distribution of the PMV value at 21:00 of the typical winter day (left-hand side) and of the typical summer day (on the right-hand side). In "Case 0", the PMV is out of the optimal range (−0.50 to 0.50) both in the winter and in the summer, typically lying around PMV = −1 in the winter (slightly cool) and PMV = 1 (slightly warm) in the summer. Although the focus of this study is the analysis of building use during evening theatre performance, simulations were also conducted at 11:00 on the same days. At this time and during the winter day, the PMV value in the former chapel shows almost the same values reported at 21:00, whereas on the summer day, the PMV value at 11:00 is of about +1.2. On the other hand, both in "Case 1" and "Case 2", the PMV is in the optimal range (−0.50 to 0.50) and very close to 0 (thermal neutrality), so in both cases and at both times, the thermal comfort is duly ensured by both technical system configurations. The most interesting message resulting from the simulations is that “Case 2” ensures the same degree of thermal comfort as “Case 1”, even if the air temperature is slightly higher (in the summer) or lower (in the winter) than with a fan–coil system, and a lower thermal stratification is observed.

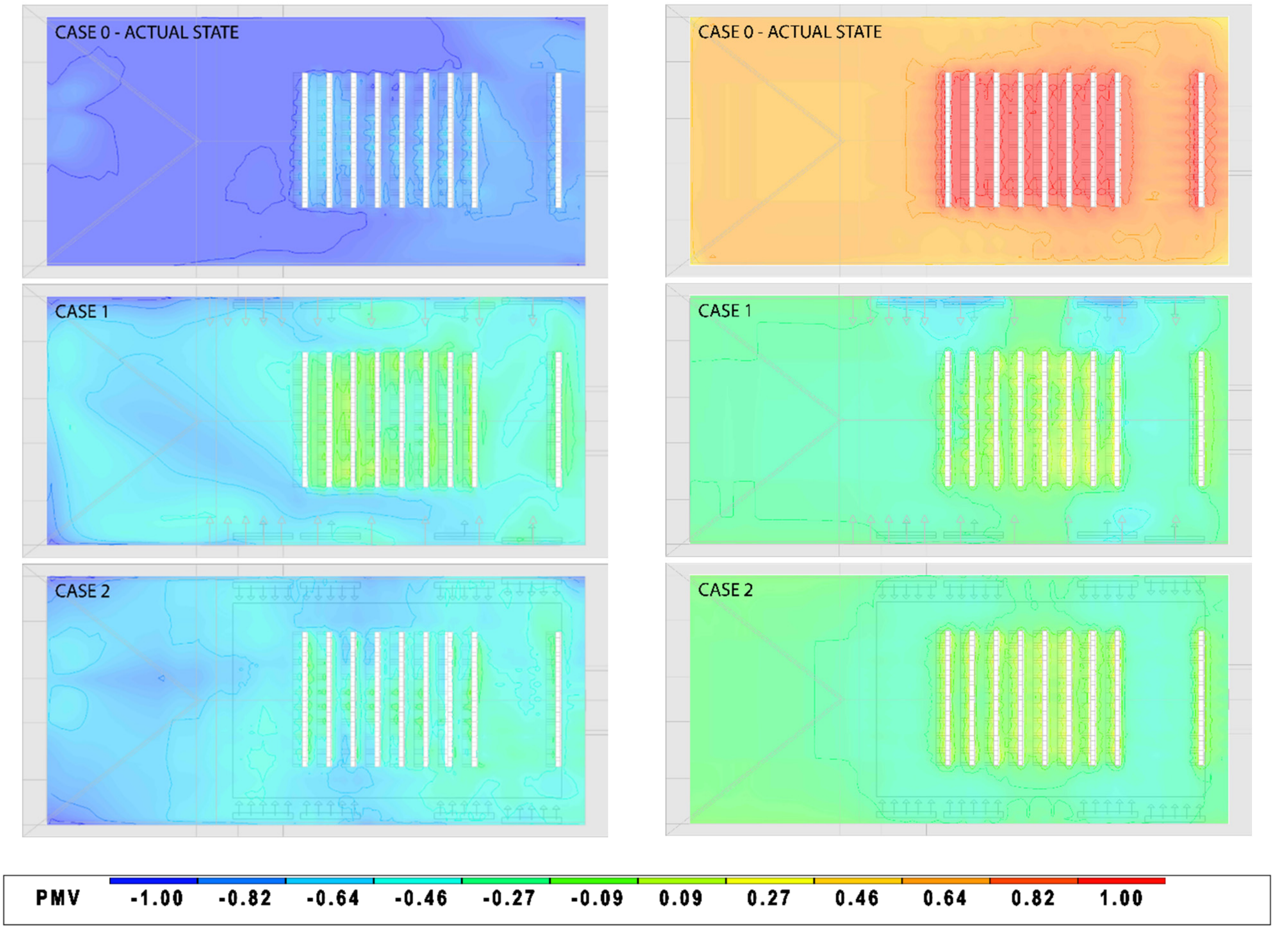

Figure 15. PMV distribution on 23 December (left column) and 1 July (right column) at 21:00.

3.5. Estimation of the Energy Performances of the Different HVAC Systems

Another analysis pointing to the benefit of the HVAC system provided in “Case 2” concerns the expected energy consumption. In this sense, a first difference is observed in terms of electricity consumption of the terminal units. According to the technical sheets of one manufacturer (SABIANA CCP–ECM 2T), a concealed underfloor fan–coil unit—with a 500 m^3/h nominal air flow rate—has four tangential fans, with a total electric power of 40 W. Because in “Case 1” there are eight fan–coil units, this solution implies 320 W of electric power absorption by the terminal units. Additionally, one should consider the electricity consumption of the water circulation pump (from the storage tank to the terminal units), estimated to be around 60 W. On the other hand, in “Case 2”, the estimated electric power absorption by the circulation pump in the radiant floor system hardly exceeds 70 W, according to a first sizing of the system (radiant surface = 70 m^2, water temperature drop = 5 °C, pipe pitch = 10 cm, and internal diameter = 20 mm corresponding to a pressure drop per unit length of around 200 Pa/m). Roughly speaking, the two systems show the same electricity consumption in the hydraulic side, but “Case 1” adds 320 W in the fan coils.

A second issue is the different COP (Coefficient of Performance) of the reversible heat pumps feeding the terminal units. In “Case 1”, in the winter, the fan–coil units require an inlet water temperature of around 45 °C, whereas the radiant floor can be fed with water at around 35 °C. In these different operating conditions, in terms of water supply temperature, and under nominal outdoor dry-bulb air temperature (7 °C), a small-capacity electric air-to-water heat pump equipped with a primary water circulation pump is expected to work with COP = 3.2 in "Case 1" and COP = 4.0 in "Case 2", according to the technical sheets (AERMEC ANK HP). By simply comparing the two COP values, and under the hypotheses that the two systems work the same number of hours, these data suggest that electricity savings of around 20% can be expected in the winter, adding up to those associated with the terminal units. In the summer, no great difference is observed in the cooling performance in the summer; indeed, the latent heat is managed through the primary air, and the two different terminal units (radiant floor and fan–coil) are fed at similar (relatively high) chilled water temperatures, as required to deal with the sensible load.

The energy consumption in the primary air distribution system was not included in this research because it performs equally in both scenarios (apart from the arrangement of the channels and air distribution vents). Furthermore, it is worth noting that "Case 1" is noisier than "Case 2" due to the fan coils, which may interfere with the outcomes of lectures and music performances; indeed, in "Case 2", the floor-level air vents were sized with an inlet air velocity below 0.2 m/s, which corresponds to a very low sound emission level.

A final very interesting comment concerns the sizing of the HVAC systems. Indeed, based on the selected primary air flow rate (2000 m^3/h), the corresponding inlet temperature (15 °C), the operating conditions of the radiant floor (70 m^2 at surface temperature of 20 °C), and the sensible cooling load (12.0 kW) are apparently not fully met. Indeed, the radiant floor provides 2800 W, whereas the primary air exchanges slightly less than 7500 "W in sensible cooling power with the indoor air. Overall, the HVAC systems in "Case 2" provide 10,300 W, i.e., around 20% less than the convective cooling loads. Despite this, the CFD simulations demonstrate that thermal comfort is still fully ensured in the occupied space. This confirms that radiant floor systems are very effective in large-volume spaces because they rely on a local radiant effect instead of heating (cooling by convection a large volume of air, thus allowing relevant energy savings.

4. Conclusions

This research has examined the comfort conditions and the thermal stratification in a former chapel that is being renovated to be used either as a conference room or as a small concert hall. The study considers the current configuration, without HVAC systems, and two possible HVAC system configurations, based on floor-level convective ("Case 1") or radiant ("Case 2") heating terminals. Moreover, the two solutions ensure the inlet of a suitable ventilation rate; however, in the first case, air diffusion take place at h = 6.55 m above the floor, whereas in the second case, fresh air is blown at the floor level (underfloor air distribution).

It was found that both a convective system ("Case 1") and a radiant floor system ("Case 2") can provide similar good levels of thermal comfort. However, some considerations lead to the preference of the radiant floor system:

- Although both configurations guarantee effective air renewal in the summer, the same thing is not true in the winter. Indeed, the configuration with the radiant floor system and floor-level air inlet provides better air distribution during the winter months compared to the fully convective system, where a primary air inlet is placed in the top of the occupied space. In fact, in the convective system, the air inlet at 20 °C at a height of 6.55 m does not allow a descending flow toward the occupants, because of the lower density of hot air. This issue does not occur in the radiant floor system, as the same air flow rate is blown near the floor;
- The radiant floor system is typically more energy-efficient. As an example, in winter, the radiant floor can be fed with water at a lower temperature (around 35 °C for supply flow and 30 °C for return flow) compared to the fan coils in "Case 1", which require water at approximately 45 °C. This means that the heat losses in the water distribution

pipes are lower in the radiant floor system, and it is also possible to produce hot water with a heat pump that would work with a higher COP (Coefficient of Performance). Additionally, auxiliary electricity-driven fans are not required for the radiant floor system, unlike the fan coils in "Case 1";

- The radiant floor system is also more efficient in terms of energy use in the summer months, as it only cools the air at lower altitudes rather than the entire volume of the building. In contrast, "Case 1" cools the entire volume of the building, resulting in energy waste.

Further studies are planned to extend the monitoring period to some summer days and optimize the HVAC system configuration and operation. Furthermore, the integration of renewable energy sources, such as solar panels, is sought to further reduce the environmental impact of air conditioning systems without negatively affecting the esthetics of the building's historical heritage.

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