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Analysis of the Impact of High-Space Building Heating System Solutions on Building Energy Efficiency

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Analysis of the Impact of High-Space Building Heating System Solutions on Building Energy Efficiency

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Abstract

The existence of stratification in high-ceiling buildings is real, but not visible or easy noticeable by humans. For field measurements, the Prayer House – The Kaunas Basilica of the Resurrection of Christ, located in Kaunas, Lithuania, was chosen, in which the temperature distribution at different heights (6 m, 8 m, 10 m, 12 m, 14 m, 16 m and 18 m) during the heating season was observed. The Basilica had radiant heaters installed at 5 m height. According to the plan of the Prayer House, CFD model was created, and the temperature distribution of the different heating (radiant heating and floor heating) systems were compared. The IDA-ICE modelling of energy consumption was conducted using the CFD results as a basis, and the economic analysis was performed based on the obtained results. The study confirmed the existence of stratification in high-ceiling buildings.

Keywords: stratification, high ceiling buildings, radiant heaters, energy efficiency, FloVent, IDA-ICE, CFD.

Introduction

Spacious buildings with high ceilings are popular in the modern world. This is what most of the world's airports, train and bus stations, shopping malls, concert and sport halls (Seduikyte et al., 2019; Hurnik et al., 2023), industrial premises, modern offices, and religious buildings look like. A significant proportion of buildings for this purpose have important social, cultural, and functional value and, therefore, face high flows of people (Zhao et al., 2014). For example - houses of prayer, like churches and Basilicas. This plays an important role for the public, who visit this type of building several times a day, and the large number of people affects the indoor microclimate, which needs to be controlled. Controlling and monitoring indoor microclimate is important for well-being of people, and to ensure that, it is necessary to create and maintain comfortable microclimate conditions in crowded areas, which are influenced by various factors: room temperature, heat distribution, relative humidity, air circulation, airspeed of movement and live beings. However, maintaining proper microclimate conditions in high-ceiling buildings can be a challenge due to the ""chimney"" effect and thermal stratification (Zhai et al., 2016). Thermal air stratification refers to the layering of air masses based on their density that occurs because of temperature differences. Additionally, indoor air quality requires high energy costs to maintain certain values in spaces with high ceilings compared to other types of premises. Nevertheless, the maintenance of microclimate conditions remains one of the most important aspects of the exploitation of buildings, and with the rapid

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increase of buildings with high ceilings, problems of air quality, thermal comfort, and energy consumption are rising (Samek et. al., 2007).

According to Xin Wang et al. (2021) the prevailing indicator of thermal comfort is typically air temperature, as it is convenient and relatable for most individuals. However, relying solely on air temperature as an indicator is insufficient and may not accurately represent thermal comfort or stress. It is crucial to consider additional environmental and personal factors to obtain a comprehensive thermal comfort assessment. Thermal comfort is influenced by six factors, encompassing both environmental and personal aspects. These factors include air temperature, radiant temperature, air velocity, humidity, clothing insulation, and metabolic heat (Wang et al., 2021). While these factors can operate independently, their combined impact significantly contributes to an individual's thermal comfort in the workplace. Since air comfort may not be perceptible at elevated heights within buildings, it is unnecessary to maintain thermal comfort throughout all vertical levels. Typically, thermal comfort is ensured within the zones where people are located, usually at a height of around 1.7 m above the ground. The work zone area is too small to notice and feel thermal stratification, which happens when two different, dense and light air meets one another. Warmer and lighter air is rising and creating warmer air layers (temperature gradient). The higher the building ceilings are, the higher the warm indoor air accumulates, which could be used to heat the building's work areas. The case study of the performance of destratification fans for large spaces obtained by Shiqiang (John) Zhai et. al., 2016 has shown that air mixers help to lower stratification. Air mixers should be hanging at least 8 m above the ground and, if installed correctly, can lower the temperature from 30 °C (at the ceiling) to 16 °C (at the work zone) (Zhai et al., 2016).

According to a study conducted in 2014 by the Building Scientific Research Information Association, the wasted energy resulting from stratification increases consistently with the temperature difference between the floor and ceiling (ΔT). The study indicates that stratified buildings are prone to excessive heating or cooling based on thermostat settings, which are often lower than the actual heat energy present in the room. The research also reveals that energy wastage due to stratification is observed in buildings with ceiling heights ranging from 6 m to 12 m, with higher ceilings leading to greater energy loss, even with the same ΔT. As taller ceilings tend to have higher ΔT, the impact of stratification is intensified, resulting in significant energy wastage in buildings with high ceilings. It is common to experience temperature differentials of up to 1.5 °C per vertical foot in stratified buildings, and this differential becomes more pronounced as ceiling height increases (Zhao et al., 2014).

The case study done by Lucyna Samek, et. al. (2007) in the church of St. Michael the Archangel in Szalova, Poland, which was built from a stone formed by an elongated rectangular nave, 10 m high and equipped with 140 radiant heaters installed 3.5 m above the floor. The power of one heater was 2 kW, and during the services, all heaters generated up to 40 kW thermal power. The heating was turned on 10 minutes before Mass and turned off after 45 minutes after the Mass was finished. The thermometers that measured the temperature were kept at ground level, 3.5 m above the ground, and 5 m above the ground. The 'church's most heated area was where the heaters were radiating their temperature. The shadowed area almost did not change its temperature due to a lack of radiation. The most heatable area of the church was irradiated, and the second was above the radiant heaters (Samek et al., 2007).

Research indicates that the radiation temperature distribution of a radiant heater with a specific power was remarkably similar in both longitudinal and transverse directions. The temperature distribution curves along the heater and across it closely align with each other.

The research conducted by N. Aste et al. (2017) confirmed that local heating is an effective solution for historic churches. This method ensures satisfactory comfort levels in specific areas while minimizing or eliminating any negative impact on artworks and building structures. The authors arrived at this conclusion by utilizing computational fluid dynamics (CFD) analysis with Fluent software (version 16.2), which was a widely used dynamic software at the time of the study. During the CFD simulation, N. Aste et al. 2017 incorporated three human manikins to evaluate the perceived comfort in terms of PMV (predicted mean vote). The PMV was assessed considering a metabolic rate typical of a seated person (0.9 met) and clothing insulation equivalent to 2.1 clo, representing winter garments with an open-front overcoat, which is commonly worn by individuals entering a church and taking a seat. To reduce computational time, only half of the model was created, and a symmetry plane was employed as a boundary condition.In the study performed by Edyta Dudkliewicz and Janusz Jezowiecki et al. (2011), it was observed that altering the suspension angle of a radiant heater had an impact on the distribution of radiation intensity, subsequently influencing the radiation temperature. To achieve the desired thermal conditions within a room, it was essential to arrange radiant heaters to ensure the most uniform irradiation of the heated surface. Manufacturers typically recommend that the operating fields of radiant heaters intersect at a minimum height of 1.5 m above the floor, while external partitions should be irradiated at a height of 2 m.

In England, a study carried out by Wenhua Chen et al. (2020), at an outdoor temperature of 0°C, showed the potential to save 32 % of energy consumption by using air mixers to disperse air temperature around the room.

A study conducted in 2017 by Magnus Wessberg et al. (2017) found that when a church is heated intermittently, a significant portion of the energy is utilized to warm up the walls. The most energy-efficient approach in buildings with thick stone walls generally involves using high-power heating systems to minimize the heating duration. Prolonged heating periods result in higher energy expenses and pose an increased risk of artifact damage due to drying. The study concluded that the heat-up time influences the various costs associated with power, energy, and overall expenses. Shorter heat-up times decrease energy costs but necessitate higher power costs. The heat-up time that offers the most cost-effective solution is the one where total costs are minimized. By conducting a step response test, the thermal properties can be determined and subsequently used to calculate the required heat-up time prior to service (Wessberg et al., 2017).

The aim of this study is to investigate the thermal stratification of the Kaunas Basilica of the Resurrection of Christ, located in Kaunas, Lithuania, with the use of field measurements and to compare the calculated energy demand of different heating systems installed in the Basilica with CFD simulations and IDA-ICE modelling.

Research Methodology

The following methods were used in this study:

- Field measurements of temperature and relative air humidity in the Prayer House.
- CFD simulations were conducted to calculate the temperature distribution – stratification within the Prayer House.
- Evaluation of the influence of stratification on the energy consumption of the building with IDA Indoor Climate and Energy (ICE) software.

The object of research

The Kaunas Basilica of the Resurrection of Christ was chosen for the research. The construction of the Basilica was started in 1934 and completed in 1940. The Basilica was reconstructed in 1952 and used as a radio factory until 1990. It is a state-protected building that has architectural, historical, and sacred properties and is included in the cultural heritage list. The Kaunas Basilica of the Resurrection of Christ was chosen because of the large spaces, which met the requirements of a high-ceiling building and the heating devices (floor heating and radiant heating) installed in it, which it was decided to compare. The building has a length of 69 m and a width of 26 m. The middle nave has a height of 30 m, while the side naves have a height of 18 m (Fig. 1).

Electric underfloor heating is installed in the entire church area, but it is not in use due to high operating costs. Currently, as a second heating system, electric radiant heaters are installed and operated, which hang 5 m above the floor (Fig. 2).

Radiant heaters were installed between the columns that separate the side and middle naves and directed towards the middle nave.

Fig. 1

First floor plan of the Basilica of the Resurrection of Christ in Kaunas (Memorial Church of the Resurrection. Technical project 292 – 01 – TP (2000))

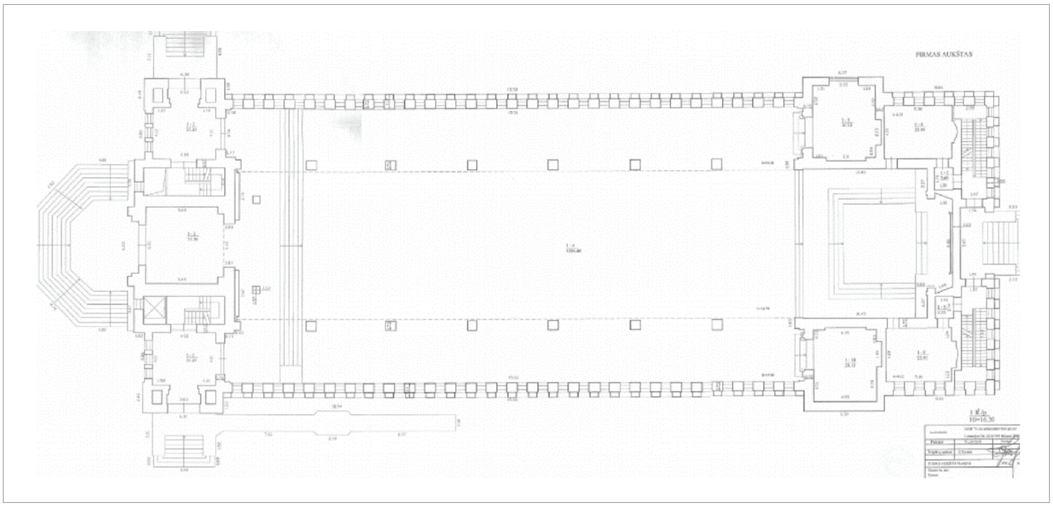


Fig. 2

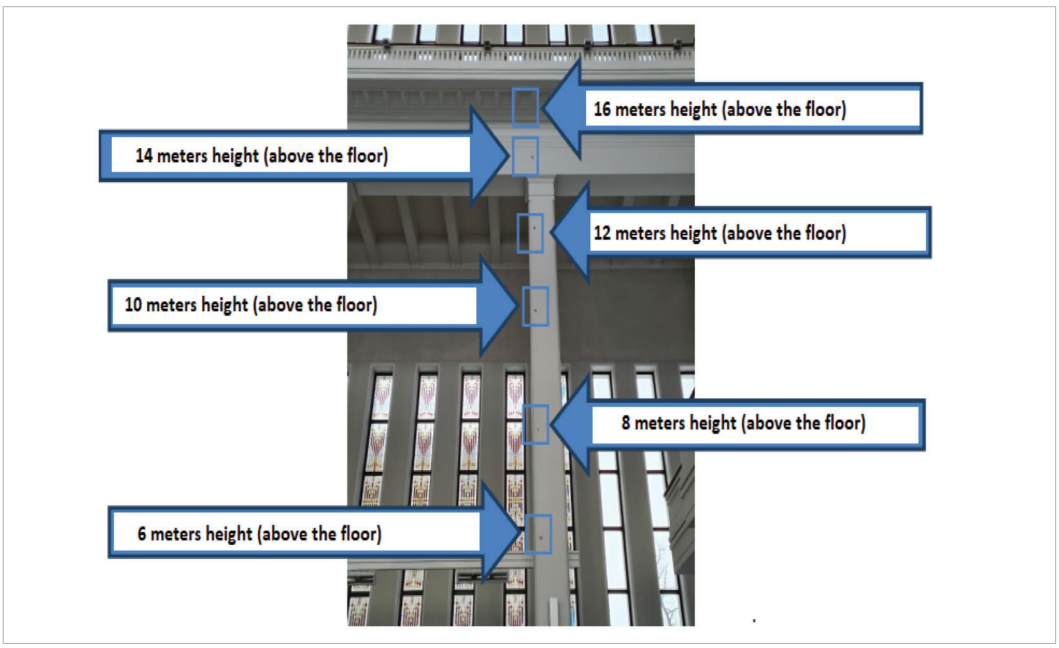
Arrangement of radiant heaters between columns

Field measurements

HOBO temperature/relative humidity/2x external channel data loggers (± 0.2 °C, ± 2 % RH accuracy) were used for temperature and relative humidity measurement. The data was collected during the heating session, from November 27 (2020), to December 4 (2020).

Fig. 3

Placement of data loggers at different heights



Since the balconies of the Basilica are at the height of 18 m, the first sensor was placed on the floor of the balcony to measure the temperature in the balcony, the second sensor was hunged 16 m above the floor and 2 m down from the balcony, which measured the temperature in the air. All remaining sensors were hunged every 2 m up to 6 m above the floor, or up to 12 m down from the balcony. The last sensor, which was placed 6 m above the floor, was 1 m above the radiant heaters, which had to be switched on during the Mass, which took place once a day at 18:00. Displayed temperature sensors are shown in Fig 3.

Computational Fluid Dynamics and IDA Indoor Climate and Energy simulations

An experimental CFD validation model was created with FloVent software to study air stratification in Basilica. FloVENT CFD software was selected based on its capabilities to forecast 3D airflow, heat transfer, contamination distribution, and comfort indices in buildings of various types and sizes.

For the identification of air stratification in Basilica, 18 sensors were modelled. Three sensors which were in the working area: the first sensor was modelled at the floor level – at the height of 0 m; the second sensor was modelled at the height of a seated person's head – at the height of 1.1 m, the third sensor was modelled at the height of a standing person's head – at the height of 1.7 m. All the remaining sensors were laid out at a height of 2 m to 30 m every two meters.

To achieve 13.0°C and 13.2°C degrees at 1.1 m and 1.7 m height, radiant heaters of 13kW power were modelled at 5 m height (at the same height radiant heaters are installed in Basilica) (Fig.4).

To Achieve 13,7 °C and 13,1°C degrees at 1,1 m and 1,7 m height floor heating system of 270 w/sq.m power was modelled (Fig.5).

Based on the FloVent CFD model, an IDA-ICE model of energy consumption has been developed. IDA ICE software can calculate the energy needs for radiant and floor heating systems. IDA ICE is a reliable and advanced simulation application that effectively replicates the building, its systems, and controllers. This ensures optimal occupant comfort while minimizing energy usage. It is a trusted and innovative tool used for detailed and dynamic multi-zone simulations throughout the year, enabling the study of indoor thermal climate and overall building energy consumption.

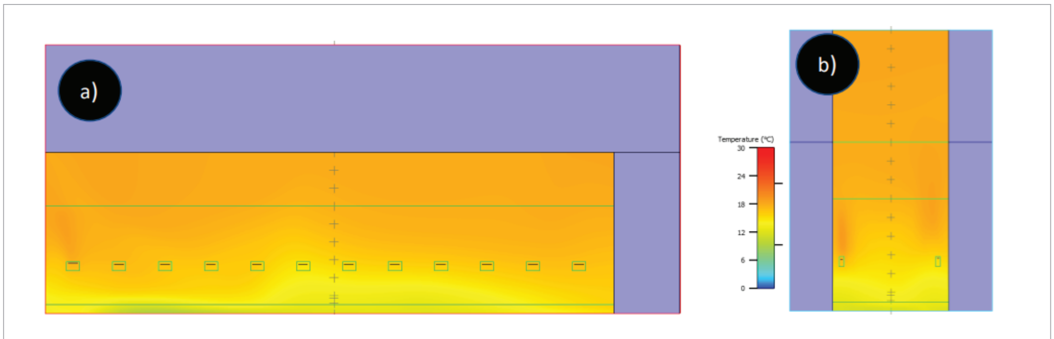


Fig. 4

Graphic representation of radiant heater temperatures. On the left (a) longitudinal vertical section. On the right (b) is a transverse vertical section

Fig. 5

Graphic representation of underfloor heating temperatures. Left (a) longitudinal vertical section. Right (b) transverse vertical section

Results And Discussion

During the Simcenter Flovent simulation of radiant heating, a temperature difference of 2.5°C was obtained between 6 m from the floor and 16 m from the floor when the working area was maintained at a temperature of 13 °C. Since the temperature in the working area was not observed in the Basilica, but after comparing the results of the field measurements and simulation between 6 m and 16 m high, it showed that the results of the simulation and study differed slightly. The difference between simulation and test temperatures was 0.66°C.

Field measurements results

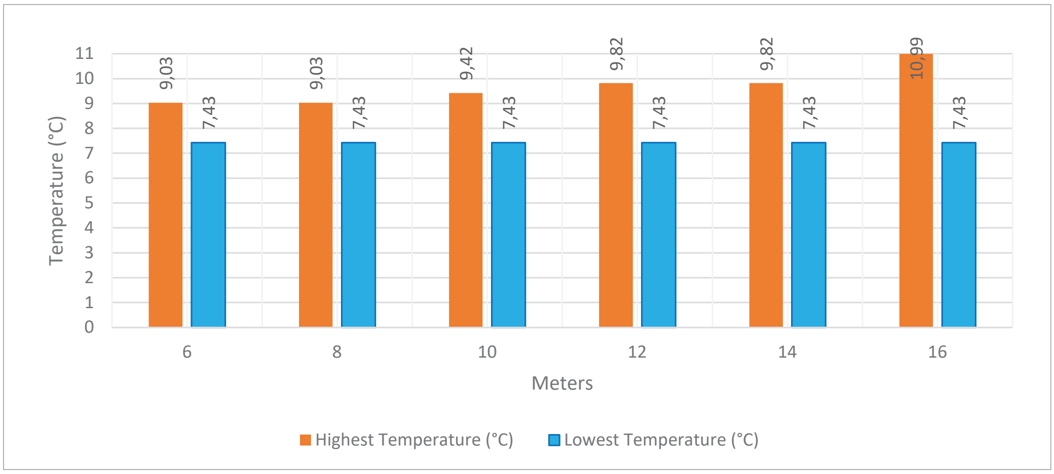
The phenomenon of stratification in the Basilica was not recorded by temperature sensors until the radiant heaters were turned on. According to the data obtained from the temperature meters, it was observed that the heating was turned on every day 30-60 minutes before the Mass and turned off when the Mass was coming to an end or when it was over. At the end of the Mass, the stratification effect weakened until finally, the temperatures in the entire Basilica were equalized to the temperatures before the Mass.

The most substantial temperature difference was observed during the November 28, 2021, field measurements. The outdoor air temperature ranged from 0 °C to 2 °C that day. However, the coldest daily air temperature occurred on November 30, 2021, from 0 °C to -6 °C. The largest daily fluctuations in outdoor air temperature were recorded on December 2, 2021, with temperatures ranging from 4 °C to -4 °C.

On November 28, 2021, the temperature differences started to differ at 18:00 (30 minutes before Mass), and the highest temperature reached was 10.99 °C at a height of 16 m. The temperature at the beginning of the Mass and the end of the Mass was 7.43 °C degrees. On November 28, 2021, a temperature difference of 3.56 °C degrees was reached. The temperature differences are shown in Fig. 6.

Fig. 6

The results of the field measurements made in the Basilica at different heights



CFD modelling and IDA-ICE energy demand calculation results

The highest temperature of the radiant heating system was 18.3 °C degrees at the ceiling of Basilica. The most significant temperature variation was observed between a height of 2.0 m and 4.0 m. The temperature increased from 14.2 °C at the height of 2 m to 15.4 °C at the height of 4 m (Fig. 4).

The highest temperature of the heating floor system was reached at a floor level – 17.8 °C degrees. The greatest temperature change was observed between a height of 0.0 m (floor level) and 1.1 m. At 1.1 m, the temperature decreased from 17.8°C to 13.7°C (Fig. 5).

The graphical representation of temperatures in different heights of radiant heaters and floor heating systems is shown in Fig 7.

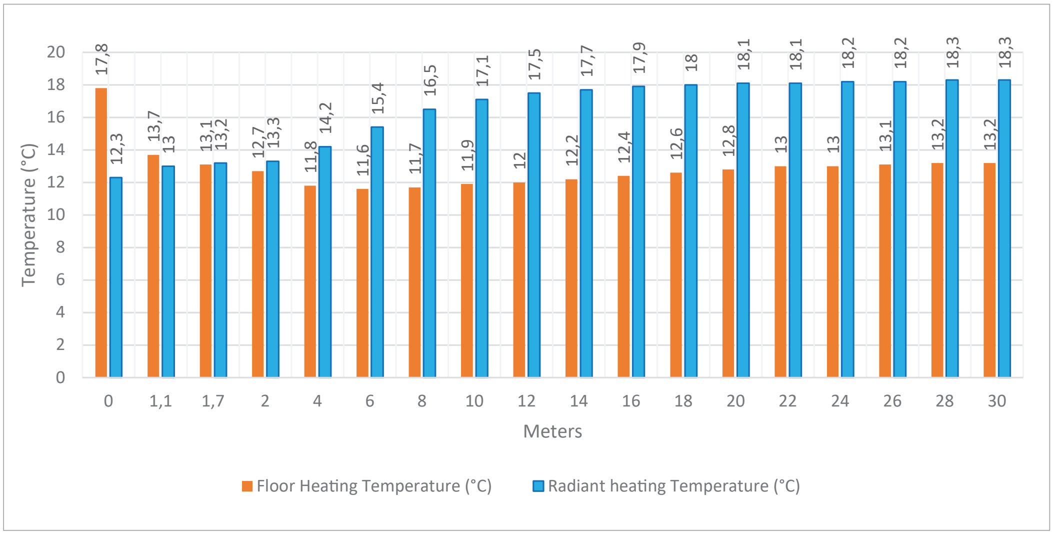


Fig. 7
Comparison of different heating system temperatures

The temperature range for floor heating showed a difference of 34.83 % between the highest and lowest recorded temperatures. Similarly, the temperature range for radiant heaters exhibited a difference of 32.78 % between the highest and lowest recorded temperatures.

Comparing the temperature differences in percentage terms, the temperature difference of radiant heaters is 2.05 % lower. However, the highest temperature of the floor the heating was recorded in the work area, while the highest temperature of radiant heaters was recorded at a height of 28 m above the floor.

Energy demand with IDA-ICE was calculated from November 1 (2020) to February 28 (2021).

Energy with radiant heaters was consumed in November 11943 kWh, in December – 12836 kWh, January – 13207 kWh, and February 11762 kWh. A total of 49748 kWh for the heating season (**Fig. 8**).

In November, floor heating consumed 10017 kWh, in December - 12879 kWh, January - 13427 kWh, and February - 11821 kWh. A total of 47964 kWh for the heating season (**Fig. 8**).

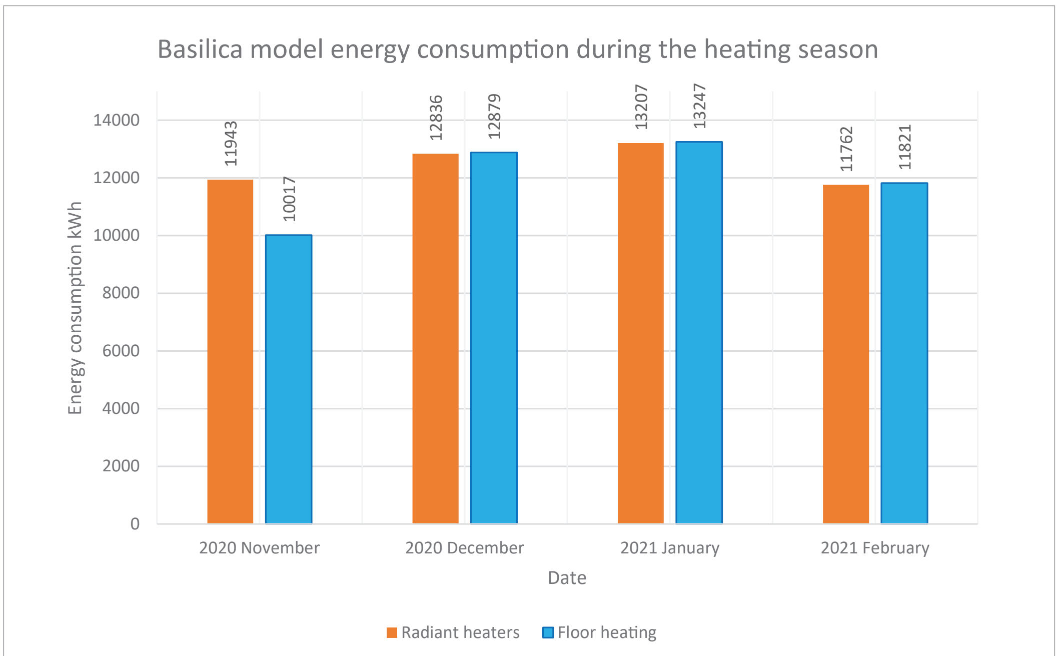


Fig. 8
Basilica model energy consumption during the heating season

Comparing the costs of floor heating and radiant heating, it was found that floor heating consumes 1786 kWh less energy per heating season, which is 3.58 %.

The energy consumption calculations conducted using IDA-ICE for simulating radiant and floor heating determined that floor heating would consume 47 964 kWh of thermal energy per heating season. On the other hand, radiant heating would consume 49 748 kWh of thermal energy per heating season, which is 1 784 kWh higher than floor heating.

Considering the energy modelling analysis outcomes, it was concluded that the heating costs associated with floor heating would be 3.58 % lower compared to radiant heating costs.

Conclusions

- Based on the field measurements conducted in the Basilica, the largest temperature difference was observed on November 28, 2021, specifically with radiant heating. On that day, the outdoor air temperature ranged from 0 °C to 2 °C, resulting in a temperature difference of 3.56 °C between the heights of 6 m and 16 m above the floor.
- The heating FloVENT CFD simulation results showed that the radiant heaters created a greater stratification above the work area - the temperature rose from 13 °C degrees in the work area to 18.3 °C degrees at the top of the Basilica. In contrast to radiant heating, the highest temperature of underfloor heating was recorded at the floor - 17.8 °C degrees, and the temperature only decreased as it rose above until a temperature of 13.2 °C degrees were reached.
- During the radiant heating FloVENT CFD simulation, the maximum temperature change was found between 2.0 and 4.0 m above the floor (1.2 °C). During the floor heating simulation, the temperature change between 2.0 and 4.0 m above the floor was 0.9 °C.
- The temperature differences between FloVENT CFD simulation and experimental measurements between 6 and 16 m above the floor were 0.66 °C degrees.
- The calculation of the energy consumption performed by IDA-ICE during the simulation of radiant and floor heating showed that 47964 kWh of thermal energy would be consumed during floor heating. During radiant heating, 49748 kWh of thermal energy would be consumed, which is 1784 kWh more than floor heating.
- Considering the results of energy modelling and economic calculations, it was found that in the case of floor heating, the heating costs would be 3.58 % lower than the radiant heating costs.

This study confirmed the theory that stratification exists in large buildings and that different heating systems cause different stratification. Based on the findings, including digital evaluation methods in the design and operation phases of both large spaces and public buildings can be recommended. Based on the literature analysis, it is recommended to use air mixers, which would help to equalize the air temperature and reduce the stratification effect. Future work on this subject should include the investigation of more detailed field measurements by adding more data loggers at the work zone and above the balconies of Basilica. Studying stratification during the summer and seeing if air mixers would help reduce air stratification during warm seasons would also be possible.

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