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Assessing Occupant Comfort in Historic Churches When Using Localised Heating Systems

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Abstract

Several church organisations have committed to net-zero by 2030 and issued guidance to heat the occupants rather than the building. Evidence shows a combination of background low grade heat with radiant systems may achieve more acceptable comfort. A model of St Mary de Haura church was created using Design Builder. A gas fired boiler and radiator system was set to 14ºC with energy consumption from local systems calculated. Heated cushions and pew mounted radiant panels could improve PMV to -0.5, even with 14ºC background heating. Utilising environmental data obtained from the actual church in this study allowed a comfort increase to -0.5 PMV with heated cushions at the same background heating setpoint. Emissions reduction in the present UK scenario was possible through the lower temperature setpoint. Background heating of 14ºC with heated cushions reduced emissions from 7,272 kg CO2e to 5,889 kg CO2e. A further reduction in emissions by 2040 was possible due to the lower carbon intensity of grid electricity. However, the continued use of natural gas limits reduction potential of the technologies use in this study. The reduced temperature setpoint does offer the potential to use alternative heating systems such as heat pumps for background heating. Such choices are aligned with UK Government ambitions for decarbonising heating.

Highlights

- Increase in PMV close to neutral by using a lower background heating setpoint and local comfrot device.
- Stability of temperature and relative humidity from sustained background heating beneficial for conservation.
- Heated cushions demonstrated higher potential to achieve localised comfort.
- Emissions are reduced through the use of electrical heating systems and potential future emissions could be significantly lower through the electrification of the background heating provision.

Introduction

Almost a third of UK carbon emissions are from heating homes and workspaces (HM Government 2021), therefore, making improvements to the existing building stock in Europe has great potential to reduce CO_2 emissions and tackle climate change (Webb 2017). The Climate Change Act 2008 set targets for the reduction of United Kingdom greenhouse gas emissions by 2050 (Committee on Climate Change 2017). The present concern is that without widespread change over the next 20 years global temperature is expected to reach or exceed 1.5°C of warming (Masson-Delmotte, Zhai et al. 2021). With 1.5°C of warming climate change has significant impact upon present living standards and will cause widespread changes to surface temperatures, humidity levels, sea level, weather patterns and food production systems. During the 2021 United Nations Climate Conference (COP26), held in Glasgow, multiple faith organisations called upon the UK Government to fulfil promises made to combat climate change and create a just and sustainable future for all (The Church of England 2021, The Lutheran World Federation 2021, Vatican News 2021, The Church of Scotland 2022). The Church of England, The Methodist Church and The Church of Scotland have all committed to net-zero by 2030 in recognition of the environmental impact of their activities (The Church of England 2020, Scotland 2021, Methodist 2022).

Localised heating and radiant systems seek to deliver heat to the occupant and hold potential to reduce emissions and the cost burden associated with traditional fossil fuelled central heating systems (Rugani, Picco et al. 2021). However, radiant systems are also known to fall short of adequate comfort in cold churches (Sustain 2013). Evidence shows a combination of background low grade heat with radiant systems may achieve more acceptable comfort levels (Historic Scotland 2015). There are studies which focus on radiant and traditional space heating technologies in conjunction with building/artefact preservation. However, few assess the technical, environmental feasibility and comfort aspects together. Past research mainly focuses on replacing central heating systems with radiant or localised heating solutions, which do not always attain high comfort levels (Camuffo 2011, Broström and Wessberg 2021). With the widespread installation of central heating in homes across the developed world, individuals routinely expect to find optimal thermal comfort widespread in public buildings. Thermal comfort is a subjective measure based on individual sensation and evaluated using several criteria: temperature, thermal radiation, humidity, activity, clothing, and air speed (Salcido, Raheem et al. 2016, Pretlove 2017, Rabanillo-Herrero, Padilla-Marcos et al. 2018). Ethnicity, health, body type, fitness and

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acclimatisation all further contribute to the complex nature of thermal comfort. Personal adaptations such as clothing, duration of stay and activity can overcome temperatures outside individual comfort ranges (Rupenheite and Sandström 2005). Those occupying a space while being sedentary or undertaking stationary light activity are most sensitive to local discomfort. When higher levels of activity are undertaken sensitivity is decreased and the risk of thermal discomfort is lowered (British Standards Institution 2006). Occupants typically expect temperatures in the range of 18-22˚C (Pretlove 2017). Measurement of comfort can be expressed using predicted mean vote (PMV). The seven point scale of PMV is: +3 Hot, +2 Warm, +1 Slightly warm, 0 Neutral, -1 Slightly cool, -2 Cool, -3 Cold (British Standards Institution 2006).

There are approximately 40,300 church buildings in the UK, taking into account all denominations and organisations (National Churches Trust 2019), with around 15,000 of these being listed buildings (Sherwood 2020). Historic churches make an important contribution to the built environment and may provide needed facilities for local communities, especially in rural and suburban areas. As churches primarily exist for worship their usage patterns are often low, with only a few events taking place during a typical week. This low building utilisation limits the amount of investment that can be justified in upgrading the building to a higher energy standard, especially when the church supports a small congregation and therefore lacks the necessary funds. In the study of an unheated church in Portugal, Silva and Henriques (2015) concluded that the existing building fabric performed well under thermal and hygrothermal fluctuations; the lack of a heating system did not mean that damage was taking place. British Standard EN 15759-1: *Heating churches, chapels and other places of worship* suggests the ideal solution is to maintain suitable environmental conditions over a constant period (British Standards Institution 2011). The repeated heating of such high thermal mass buildings often introduces degrading processes in high value artefacts such as paintings, fabric, artwork and musical instruments like the organ (Bencs, Spolnik et al. 2007). Although, sacred artefacts and materials in churches have adapted over time to the prevailing internal environmental conditions. To avoid further damaging these items Cannistraro, Cannistraro et al. (2012) suggest that the current internal environment be maintained rather than those deemed ideal for the material or objects.

In 2002 the European Union funded the Church Friendly Heating programme. Camuffo, Pagan et al. (2010) reported on three technologies fitted in two Alpine churches in Italy, both historic in nature (14th and 15th century construction) and located at high elevation. The existing heating system was ineffective at proving thermal comfort to the occupants. Warm air space heating was in use but thermal stratification limited the amount of heat available at the floor level. It was determined that the church would be left to operate without space heating in the prevailing climatic conditions it was accustomed. Radiant and localised heating technologies were installed to provide thermal comfort to the occupants, without the need to heat the entire volume of air. This approach to heating had the potential to reduce damage to the building fabric, internal components and artefacts contained within the church.

Methodology

A large, part 12th century church constructed of cean limestone and flint (St Mary de Haura, Shoreham-by-Sea, UK) was selected as typical of a well used urban historic church representative of south east England. Building utilisation is around 15 hours a week at present. A traditional hot water boiler and radiator system is present in the church with timed or manual control. Typically a 1 hour warm-up period is used prior to activity taking place in the church. The church has 48 pews with a smaller defined area off to one side of the altar for more intimate worship settings. There is no zonal control on the heating system and some high level radiators have been isolated to limit heating the unoccupied areas of the building.

A model of the church was created using Design Builder software, a graphical interface for EnergyPlus (Figure 1). All simulations were undertaken using this software to assess energy consumption, emissions and comfort. The detailed HVAC option was used in the model, scheduled natural ventilation, occupation schedules defined and windows were lumped on surfaces. A gas fired hot water boiler and radiator system was set to provide either 14ºC or 20ºC background heat for the church model. The heating schedule was for operation four times a day, representing two hour blocks of operation when the church is usually occupied.

Simulations were undertaken at a setpoint of 20ºC for the main zone of the church using radiators and an air source heat pump with radiators. The setpoint was then reduced to 14ºC setpoint with radiators and energy consumption

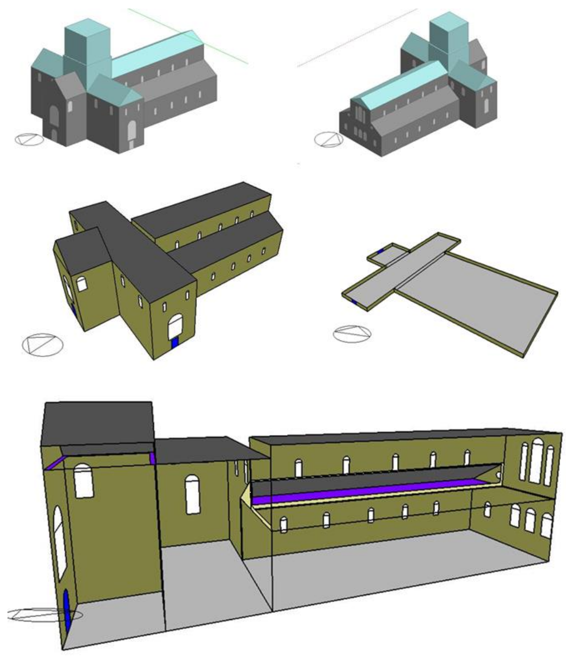

Figure 1 DesignBuilder model of St Mary de Haura. Total floor area 536m² (291m² unconditioned)

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from three local/radiant systems was calculated from equipment ratings. A gas boiler set to provide 14oC was used in the simulation with three different fictitious loads added in from heated cushions, low temperature radiant panels and high temperature radiant panels mounted above the main occupied zone.

Two occupation levels 'minimum' and 'maximum' were used to indicate the occupancy level of the building, simulating the demand responsiveness of the localised heating system to occupation levels. Minimum occupation infers only half the radiant system was energised for reduced occupancy levels, or maximum for the whole system being energised. These fictitious energy loads are added into the main zone of the church as additional energy considered in the simulation. For low temperature systems such as radiant panels and heated cushions this additional energy represented a small amount. For high temperature systems such as radiant emitters placed high on the wall, there was greater energy input to the occupied space.

A semi-automated PMV Excel calculator from da Silva et al was used to derive an adjusted PMV from the simulation results which took into consideration the local comfort system (da Silva, Pires et al. 2014). Metabolic activity, clothing value, air temperature, radiant temperature, water vapour pressure and air speed were all necessary input data for the calculator. While PMV is generated as part of the Design Builder software simulation it was important for the next step of the study to verify if PMV predictions from the software matched the manual calculation method. Results were found to be in close alignment.

A method was developed to understand the effect radiant systems would have on local occupant comfort. An online mean radiant temperature (MRT) tool developed by The Center for the Built Environment was used to generate localised temperature data for use in the calculation of PMV (Center for the Built Environment 2016). A box could be dimensioned on the MRT calculator with a radiant surface placed on one or more surfaces. The occupant – seated or standing, radiant surface temperature, air temperature and presence of walls were all controllable options within the simulation controls. Running the simulation resulted in a coloured temperature map within the box. A 2m x 2m box was created in the MRT calculator representing low temperature systems located near the occupant. While a large box was made with exact dimensions of the main zone of the church and radiant sources mounted 6m high up on the walls to replicate high temperature radiant panels.

Background temperature of the dimensioned box was set to 14°C. Figure 2 shows the set up for a radiant panel operating with a surface temperature of approx. 50°C. High temperature panels used a surface temperature of 900°C. Heated cushions operated at a temperature of 38°C. A temperature was taken approximately 35-40cm away from the panel surface, representing the typical distance to the torso of a seated occupant 164 cm tall.

These new radiant temperatures were then used in the Excel PMV calculator with the temperatures and relative humidity generated in the Design Builder simulations. PMV for January 4th at 10am and 5pm were calculated at activity level of 1met and 0.76clo (clothing value). Temperature and relative humidity data collected from the church in 2019/2020 was utilised to calculate the PMV

Figure 2 Mean radiant temperature simulation tool from the Center for the Built Environment

using the same method as described above.

Results were plotted to demonstrate the potential comfort improvements calculated using the local comfort systems. Cost and emissions have been calculated to demonstrate the advantage of local heating systems over traditional central heating systems. Calculations were undertaken using the minimum occupancy simulations, to reflect the reduced occupancy many churches currently experience. Total cost amounts are based upon Energy Saving Trust figures for 2020 and 2022: Low cost: gas @ 3p/kWh + electricity @ 17p/kWh, Medium cost: gas @ 10p/kWh + electricity @ 34p/kWh (Energy Savings Trust 2020, Energy Savings Trust 2022). Emissions are based upon UK conversion factors 2022 (gas: 0.2 kg CO2e/kWh, electric: 0.19338 kg CO2e/kWh) and projected emissions for 2040 (electric: 0.016 kg CO2e/kWh) (UK Government 2022, Department for Business 2023). The annual heating fuel consumption obtained from the Design Builder simulation was used to calculate emissions and cost.

Equation 1:

$$Total\ kWh\ fuel * \ kg\ CO2e/kWh$$

Equation 2:

$$Total\ kWh\ fuel * Cost/kWh$$

Results

The adjusted PMV calculations, taking into account the effect of the local heating system in the MRT tool, allowed an improved PMV figure for occupant comfort. In some cases (see Figure 3) the PMV could be adjusted close to zero, where the majority of occupants would experience neutral or stable comfort. Using a hot water radiator heating system set to 14°C with heated cushions or pew mounted radiant panels could improve PMV to -0.5 or -1.5 respectively. High temperature radiant panels mounted 6m high on the walls were less able to provide improved comfort at 14°C background temperature. Minimum and maximum did not affect the outcome greatly, but did account for more energy being added into the zone.

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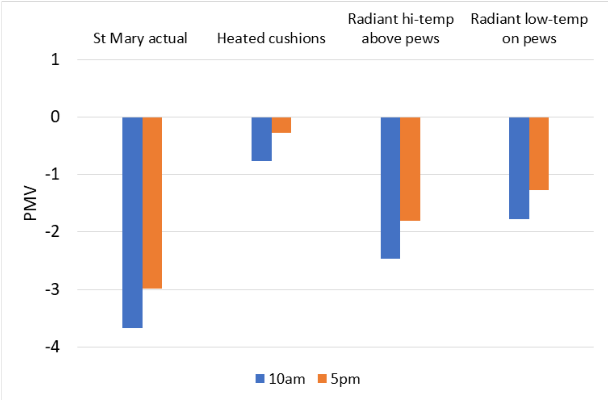

Figure 4 St Mary de Haura 14ºC background heating, 1met, 0.76 clo, local adjusted PMV on January 4th 2020

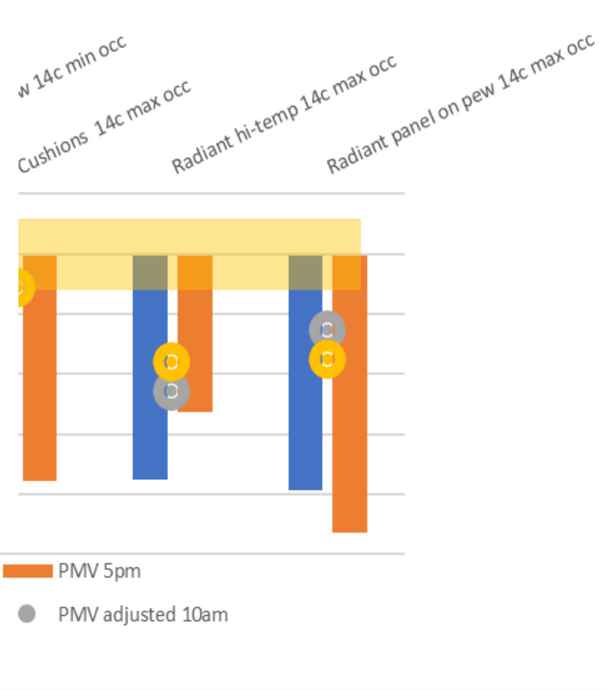

Figure 3 PMV adjusted for radiant systems (dots). 1met, 0.76 clo, January 4th at varying occupation levels

When the same method of adjusted PMV is applied to the environmental data captured from the church in January 2020, improved comfort for each system can be plotted (Figure 4). The calculated PMV in St Mary de Haura on 4th January is -2.98 or less. During the heating period of the 4th January the highest air temperature recorded was 18ºC. This temperature was not uniform across the monitored area of pews. Therefore, the calculations demonstrate that with the lower background temperature recorded at 10am and 5pm a localised heating system active in the church could raise PMV up to -0.27, based upon the calculation method presented.

Calculation of total energy consumption, operational cost and associated emissions are compiled in Table 1. GB-R indicates a gas boiler with radiators. ASHP-R is an air source heat pump with radiators. Local comfort systems are as follows: HC – heated cushions, HT RP – high temperature radiant panel and LT RP – low temperature radiant panel.

It can be seen that the modelled ASHP striving for the 20ºC setpoint option provides considerable energy saving over the conventional gas boiler and radiators. Reducing the setpoint to 14ºC and using heated cushions or low temperature radiant panels produced the second largest energy saving, compared to system A. In a low cost energy scenario a gas boiler (system A) performed the best when the setpoint was 20ºC. If medium tariff costs were experienced systems A, C and E remain the most cost effective.

Calculated emissions using 2022 UK carbon emission factors resulted in the ASHP (system B) returning the lowest figure, followed by system C. Projecting emissions forward to 2040 for all systems resulted in the all electric system B returning a significant reduction in emissions. Those systems still using fossil fuels in combination with electrical local comfort systems experienced smaller reductions. When considering emissions, the future benefit of utilising electricity for heating is apparent.

These results are promising, indicating that personal comfort devices operated by the user provide additional comfort at low background temperatures. However, further work is required on the effect of radiant asymmetry associated with close proximity to cold walls and pillars, and analysis of whole body PMV.

Discussion

Despite construction utilising high thermal mass materials the sporadic nature of church services results in an environment which is often below human comfort levels (D'Ayala and Aktas 2016). The outcomes of this study are favourable towards the use of local electrical heating to increase comfort for occupants in historic churches. There is sufficient evidence in existing research that historic

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Table 1 Consumption, cost and emissions from heating options

	System for main zone	Gas kWh	Electricity kWh	Total energy saving over A	Low cost (£):	Medium cost (£):	Emissions 2022 UK kg CO2e	Emissions 2040 UK kg CO2e
A	GB-R @ 20ºC	36,360	-	-	1,091	3,636	7,272	7,272
B	ASHP-R @ 20ºC	-	16,294	20,066	2,770	5,540	3,151	261
C	GB-R @ 14ºC + HC	25,839	3,728	6,793	1,409	3,851	5,889	5,227
D	GB-R @ 14ºC + HT, RP	25,218	8,145	2,996	2,141	5,291	6,619	5,174
E	GB-R @ 14ºC + LT, RP	25,333	4,999	6,028	1,610	4,233	6,033	5,147

churches frequently experience poor comfort levels, despite active central heating systems. The simulations undertaken in Design Builder verify that PMV is lower than expected from a heating setpoint of 20ºC. Using the data derived from the MRT tool to adjust PMV reveals that comfort can be improved using local heating systems.

There is clear direction from the Church of England that the future of church heating could be electric, rather than fossil fuel based, and churches should seek to heat people not the building (The Church of England 2022). Furthermore, electricity is widely available, even in very rural settings. One radiant technology not represented here is gas powered radiant heaters. These do feature in many churches, as gas is considerably cheaper as a source of thermal energy. However, electricity is more widely available and burning gas directly in the church increases the internal moisture burden.

The CIBSE benchmark for neutral comfort is shown in Figure 3. It should be noted that this comfort level is calculated at slightly higher activity and clothing values, with a temperature between 19-21ºC. It is important to realise that a radiant system achieving acceptable local comfort at 14ºC background temperature may still require occupants to wear more clothing layers. This study has looked at a lower clo value than CIBSE, to represent the fact that people might expect public buildings to be warm and dress in lighter clothing, as they do at home. As churches look to expand the number of uses for the building, potentially becoming available for community use, being able to host varied activities at suitable room temperatures is an important consideration. Activities like social dancing or exercise classes would benefit from lower room temperatures. At present many churches have heating systems based upon hydronic radiators which are either on or off, severely limiting control of temperature and comfort levels. Where necessary the background heating system could be used to increase the air temperature in the short term. The introduction of a sustained low temperature with localised heating may improve local comfort without compromising environmental sustainability. The stable temperatures are also preferred for conservation of artefacts and artworks within the space.

Although the PMV calculations are undertaken using background heat sourced from a gas-powered boiler, the lower energy demand shown for the ASHP at 20ºC demonstrates using a heat pump system to generate and maintain the 14ºC background heating level has great potential to reduce emissions, especially in the future 2040 emissions scenario. With the UK Government keen to transform the way buildings are heated, technologies like heat pumps, ideal for low temperature heat output over sustained periods of time, appear to be useful in the context of church heating (The Department for Business 2020). Emissions reduction potential clearly indicates that electric heating and electric personal comfort devices used to increase localised comfort levels will dramatically reduce the carbon emissions associated with heating churches.

It is accepted that busy churches with many periods of occupation during the week may find it is better practice to keep the building fabric at a higher background temperature, thus ensuring radiant asymmetry is reduced. The Diocese of Chichester launched the Energy Stewardship Programme in 2016 to address the needs of the local congregation and provide facilities that could attract wider use from the local community (Diocese of Chichester 2016). Being able to heat the space efficiently and without prohibitive cost could increase the utilisation of the building throughout the whole week. Evidence shows that in the case of Kilmodan church, in Scotland, an air source heat pump (ASHP) could deliver more than double the heat output of the current system at the same 4p/kWh cost (WhamArchitecture 2014).

With the concerns over the future sustainability of churches, both in terms of building utilisation and environmental impact, this research is valuable to demonstrate that the high cost and high emissions from central heating systems can be reduced through the use of

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personal comfort systems like heated cushions, which offers solutions for both fixed pews and moveable seating.

Conclusion

This paper has demonstrated that using local and radiant systems has improved calculated PMV, at certain clothing and activity levels, in both a software model and when utilising environmental data from the case study church.

Stable lower background temperatures align with conservation needs of historic churches and artefacts. 14ºC reduces energy consumption and associated cost from the central heating system. Heated cushions held the greatest potential to reach neutral comfort levels for the occupant, even with the low background heat.

Carbon emissions from the combined system of gas boiler at 14ºC and local comfort system could be reduced by 2,000 kg CO_2e over a gas boiler set for 20ºC. The lower cost of gas prevented the other combinations of background heating and electric local comfort system returning lower operational costs. However, for a comparable cost there appears a benefit in comfort by using local comfort devices in combination with lower background heating. If the background heating is provided by a different system, for example a heat pump, there may be potential for cost reduction. Combining a heat pump set to maintain a low level background temperature with localised electric heating options appears to be a natural next step as a suitable hybrid system able to provide stability and comfort with lower emissions than natural gas boilers.

Future emissions reduction potential is increased when electric systems are specified. Having an all electric heating system would significantly reduce the emissions in the 2040 emissions scenario. Lower background temperatures in the building could be helpful for certain activities, allowing more flexible use of the space. Busy churches may find the temperature too low to combat radiant asymmetry and require methods to address whole body comfort if occupants are regularly seated at low activity levels.

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