An evaluation of heating strategy, thermal environment and carbon emissions in three UK churches

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Abstract

Churches are an important part of our cultural heritage, and many now provide community activities in addition to worship. This requires reconsideration of environmental needs, to provide efficient, comfortable and healthy conditions.

Churches contain many culturally valuable artefacts and materials that are sensitive to the environment, yet have survived for centuries in their natural conditions. Most churches in the UK have had heating installed, causing damage as a result of fluctuating conditions during intermittent occupancy.

This study evaluates environmental needs for comfort and conservation and shows both can be optimised if carefully considered.

The findings show that system selection has a significant impact on energy consumption, and that occupancy issues must be considering. In order to reduce carbon emissions, responsive heating systems are most appropriate in intermittently occupied churches, and in high occupancy churches, continual use heating systems, coupled with thermal mass are more appropriate strategies to limit carbon emissions.

Keywords

Building conservation, building preservation, church heating, environmental design, thermal comfort, energy efficiency, carbon emissions, thermal stratification.

1. Introduction

Historic church buildings are an important part of our cultural heritage, and their preservation, in architectural and historical terms is of paramount importance. The number of operational churches in the UK is declining, primarily as a result of an increasingly secular society, and those that survive, often do so by providing community access for a number of activities in addition to religious worship. This change of use often requires reconsideration of the environmental needs and the upgrading of building services to provide comfortable and healthy internal conditions.

Most European churches are historic buildings where people congregate intermittently for short periods of time with relatively long intervals in between (Varas-Muriel, 2014). The historical, and natural, environmental conditions inside church buildings are determined primarily by the external climate at that location, the building structure and size and the materials used in their construction (Varas-Muriel, 2014; Napp and Kalamees, 2015).

Historic buildings are a particularly important and vulnerable building category, and they provide challenges in conservation and comfort terms (Makrodimitri et al, 2011). Churches contain many kinds of culturally valuable artefacts and objects, including paintings, frescos, metals, textiles and composite objects like organs. All of these can be significantly affected by conditions of temperature and relative humidity (Camuffo and della Valle, 2007) and are deteriorating primarily through the impact of an artificial climate produced by indoor heating in order to provide modern demands for comfort (Samek et al, 2007). The worst impacts are caused by environmental fluctuations that stress the building fabric and sensitive objects (Napp et al, 2015; Makrodimitri et al, 2011; Camuffo and della Valle, 2007; Feilden, 1982).

Historic churches were originally unheated and some of them still are (Samek et al, 2007). Cold churches have been used for centuries (Camuffo and della Valle, 2007), and even in cold climate countries there are still churches that operate without heating (Brostrom and Hansson, 2007). Most churches were never designed or built to be as warm as we expect them to be today (Makrodimitri et al, 2011), although fireplaces have been found in a very few churches in the UK. It has been suggested by many conservation authorities that in order to reduce the degradation of sensitive materials and artefacts, the best option is to have no heating (Samek et al, 2007). Artefacts in many churches that are unheated have lasted well for centuries and are in generally good condition (Camuffo and della Valle, 2007). However, the natural environmental conditions in churches do not generally satisfy the requirements for human thermal comfort, particularly in the winter, and so since the early twentieth century, a significant proportion of churches have had some form of heating installed (Varas-Muriel et al, 2014; Napp and Kalamees, 2015; Makrodimitri et al, 2011).

The European Standard that deals with the guidelines for heating churches, chapels and other places of worship (BSI, 2011) states that churches in cold climates may be heated in order to provide thermal comfort for the occupants, improve environmental conditions for the conservation of the building and its contents, or a combination of the two. The standard provides guidance for decisions relating to the building, the indoor climate specification with respect to comfort and conservation, heating strategy and specification, and post-installation evaluation.

Churches typically have large volumes and massive uninsulated masonry walls, which provide environmental challenges (Makrodimitri et al, 2012). Heating these large volumes of cold and damp air is inefficient, since people only occupy a very small proportion of the volume and warm air tends to rise to areas of the space that are unoccupied (Varas-Muriel et al, 2014).

In terms of sustainability, churches therefore constitute a problem, partly because they also often escape the most stringent requirements of legislation (Camuffo, 2011). English Heritage suggests that it is important to make every reasonable alteration to the existing historic building stock in order to increase energy efficiency in ways sympathetic to their historic character (English Heritage, 2001; 2004). The Church of England reports that space heating accounts for the majority of carbon emissions from churches, with electric light following close behind (Makrodimitri et al, 2011; Church of England, 2008), and has been proactive in setting out policy for reducing the carbon footprint of churches and associated buildings in their seven year plan for achieving an 80% reduction in carbon emissions from churches by 2050 (Church of England, 2009).

In more modern churches, built from the mid 20th century onwards, guidance on practical considerations for environmental control does not generally consider the impact of the environmental conditions on sensitive materials and artefacts, primarily, it is thought, because these contemporary places of worship contain relatively few objects requiring preservation compared to traditional historic buildings. In his comprehensive guidance on the modern church, written in the mid-1950's, Mills sets out practical considerations for modern church buildings and covers strategies for heating and ventilation to ensure thermal comfort and health, artificial lighting, and insulation levels for thermal efficiency and sound insulation, but no mention is made of humidity control (Mills, 1956).

Continuous heating is sometimes considered a favourable strategy that avoids cyclical changes in temperature and relative humidity. Intermittent and rapid heating is also sometimes claimed to be a good strategy as it is considered that the changes are too short-term to cause damage. However, these short-term changes in temperature still cause sharp variations in relative humidity, which can be harmful (Camuffo et al, 2010). A substantial body of work has shown that, for most materials, relative humidity is a more significant factor than temperature (Kirby Atkinson, 2014). This is in direct conflict with thermal comfort, since human occupants are far more sensitive to temperature than relative humidity.

A relatively limited number of studies have been carried out in churches in the UK that evaluate the thermal environment and carbon performance of church heating strategies.

The primary *aim* of this study was to consider the factors affecting performance of heating systems in churches, including, broadly, the heating system and control strategy, the responsiveness of the building fabric, and the impact this has on environmental conditions affecting occupant comfort and the conservation of sensitive artefacts and materials.

The primary *objective* of this study was therefore to enable the selection of appropriate heating systems in order to optimise occupant comfort and the preservation of sensitive objects and artefacts in church buildings. This required the consideration of heating system strategy, resource consumption, building volume and fabric thermal mass and occupancy patterns and behaviour.

Whilst the scope and scale of this project was limited by time, access requirements and resource constraints, the findings provide useful basic guidance on a number of key parameters, particularly for those involved in the conservation and preservation of these buildings together with those who occupy and maintain them.

1.1 Environmental requirements

The thermal comfort of the occupants in a building is dependent upon four environmental factors and two personal factors. These factors include the air temperature, mean radiant temperature, relative humidity, air velocity, the activity levels of the occupants and the levels of personal clothing. In this study the environmental conditions of air temperature and relative humidity were measured. The optimal conditions required for the thermal comfort of occupants is relatively well established, with typical ranges of temperature being between 16°C and 22°C (CIBSE, 2006) and ranges of relative humidity being between 40% and 80% (Makrodimitri et al, 2011, 2012).

The optimal environmental conditions for the conservation of materials and artefacts in historic buildings are difficult to define, and difficult to find in the literature, primarily due to the wide range of conditions required by different classes of artefact. In many sources, recommendations for conservation of historical artefacts relate only to relative humidity ranges and those commonly quoted are between 30% and 60% (Makrodimitri et al, 2011, 2012; Erhardt et al, 1997). In fact, the European Standard for the conservation of cultural property (BSI, 2011) describes relative humidity as the most critical parameter for conservation requirements and it should be kept at a defined and stable level. Temperature is also considered, and has both a potential direct and indirect (due to relative humidity effects) impact on heritage items and so might be specified to meet relative humidity requirements or to keep conditions above the dew point temperature in order to eliminate condensation.

Kirby Atkinson (2014) has published temperature and relative humidity conditions required for protecting museum and galleries collections. The author recognises that church buildings have their own set of requirements, and suggests that keeping relative humidity between 40% and 60% and temperature between 16C and 25C is acceptable for the preservation of hygroscopic materials (Kirby Atkinson, 2014).

Another comprehensive review of recommended environmental conditions has been published, and this data is indicated in Table 1 (Cardinale et al, 2014). These figures broadly corroborate with a further comprehensive set of data (La Gennusa et al, 2008) but there are some variations, which are acknowledged, primarily due to the latter focusing on the conservation of artefacts in museums, which have different environmental requirements and levels of control compared to typical church buildings.

In order to satisfy the required conditions for the conservation of most artefacts found in churches, it can be concluded that temperature should be kept within a range of 15°C to 25°C and relative humidity within a range of 35% to 65%. These ranges, particularly in terms of temperature, are based upon a number of literature sources that deal with church buildings and museums and galleries, and as such, it is recognised that in practice the lower temperature range of 15°C is not easily achieved in church buildings where for significant periods of time, when churches are unoccupied, the internal temperatures will revert to colder ambient external conditions. Nonetheless, in order to deal with material deterioration, particularly in buildings that were traditionally unheated but more recently have heating regimes imposed on them, the conservation envelope attempts to identify a safe and practical range of conditions for UK churches which deals with most materials and artefacts commonly found in these buildings.

Using the data collected in the literature, the environmental conditions that satisfy both comfort and conservation are indicated in Figure 1.

European Standards exist that deal with the conservation of cultural property and the specification for temperature and humidity to limit damage to hygroscopic materials (BSI, 2010a). These standards primarily deal with the determination of temperature and relative humidity ranges and propose a methodology for general specifications to limit environmental damage to objects and artefacts, but no precise values are provided. The methodology adopted, requires an assessment of the *historical climate environment* in order to determine the average and range of conditions to which objects have been acclimatised over a period of at least one year.

1.2 Heating systems and Indoor Climate

Crude heating systems began to appear in churches in the first half of the 19th century and early systems were generally localised fireplaces or central systems, retrofitted to an existing building, often adding historical richness to the buildings that they have now serviced for so long (Makrodimitri et al, 2011). Contemporary heating systems are numerous and church buildings are often dealt with inappropriately, leading to draughts, thermal stratification, condensation, deterioration and elevated energy consumption (Makrodimitri et al, 2011). Different heating systems and regimes are used in churches, the choice usually being made between warm air, radiant heaters, water filled radiators, under floor and pew heating (Samek et al, 2007; Bordass and Benrose, 1996).

Heating is a major environmental factor in providing appropriate environmental conditions in historic buildings and heating *regimes* can be divided into three categories: no heating, intermittent heating and continuous heating (Makrodimitri et al, 2011; BSI, 2011). Heating strategies are also often categorised in terms of two main *systems*: central heating which heats the whole volume of the building, and localised heating where the general volume is kept at ambient conditions and heating is provided locally for the occupants of the building and the space that they occupy (Camuffo and della Valle, 2007; Makrodimitri et al, 2012).

Central heating has the advantage of utilising known technology and ensures that everywhere within the building is comfortable. However, as heat tends to rise, warm air moves to the upper parts of the building, which are unoccupied by people and often contain most of the sensitive artefacts that are potentially damaged by this strategy (Camuffo and della Valle, 2007). As the air in these upper areas increases in temperature, the relative humidity drops. These sharp changes in conditions are what cause most of the damage, particularly to artefacts that have a high thermal inertia, that are prone to cracking, flaking and blistering (Camuffo and della Valle, 2007). It is the fluctuating conditions that have the greatest impact on artefacts, and stable conditions, either ambient or continuous heating, have a significantly lower potential for damage. Common central heating systems include forced air systems and hot water radiator systems because they are relatively low cost to install and they can heat large volumes of air relatively quickly (Varas-Muriel et al, 2014).

Warm air systems are found in many churches and these often tend to induce significant variations in indoor hygrothermal conditions that often result in temporal and spatial stratification of temperature and relative humidity (Makrodimitri et al, 2011). Thermal comfort of the occupants is often not achieved, as air at low level remains cold and heat accumulates in the upper parts of the building (Varas-Muriel et al, 2014).

Localised heating has often been installed in churches primarily for reasons of cost. It makes better use of energy by focusing heat where it is required for comfort while promoting conservation since sensitive artefacts remain in their natural environment (Camuffo and della Valle, 2007). Thermal comfort is often lower than with central heating because various systems only provide heat to certain parts of the body, such as heads and shoulders, whilst ignoring other parts, such as legs and feet (Camuffo and della Valle, 2007). Radiant emitters and pew heating are common solutions and these provide a practical solution for ensuring occupant comfort and conservation (Camuffo and della Valle, 2007). Localised systems are found regularly, and include radiant heat emitters, forced and fan convectors, flueless heaters and stoves (Makrodimitri et al, 2011).

If churches are only intermittently heated, the congregation themselves bring in a significant moisture load which then becomes absorbed by the warm air. When the congregation leaves then the air cools and can no longer support this moisture vapour and water condenses on cold surfaces below the dew point temperature. Thus, cyclical temperature changes are to be avoided, and the best approach is to heat only moderately and to heat only those areas required for thermal comfort, for instance with radiant heaters (Bordass and Benrose, 1996; Thomson, 2005).

1.3 Previous case studies

A number of European studies have demonstrated the potential consequences of the use of traditional warm air heating systems and their negative impact on the conservation of church heritage. Alternative heating systems, which have less impact on both conservation and energy consumption, have been utilised in many churches, including radiant heating, underfloor heating and pew heating, all designed to raise temperatures local to the church occupants without significantly impacting on the overall indoor environment (Varas-Muriel et al, 2014).

One of the most significant, and widely reported, European studies of church heating system strategy is the European Commission (EC) funded Friendly Heating project. The project addressed a number of problems that are caused by continuous or intermittent heating of historic churches, and the impact that this has on occupant comfort and artefact preservation (Camuffo, 2007, 2011; Camuffo et al, 2010). The project sought a heating strategy solution where thermal comfort and artefact conservation were both satisfied. The solution adopted requires localised heating in the form of low temperature radiant heaters placed in pews. These provide comfort only in the zones that are occupied by people and ensure that the remaining areas of the church are kept in stable conditions, for the preservation of artefacts, in similar ambient conditions to those they have experienced for centuries previously (Camuffo and della Valle, 2007; Camuffo, 2007, 2011; Camuffo et al, 2010). It is suggested that this strategy works well in mild climates, but in colder climates the occupants might need to adapt by wearing more heavy clothing during the coldest periods. A number of other, broader, conclusions of the Friendly Heating project have also been made. Conservation needs and energy saving are intrinsically linked and both are opposed to comfort. A compromise between conservation and comfort is required but conservation should have priority. Improving the church envelope, levels of insulation and airtightness are important and only once these have been dealt with should the heating strategy and system be considered; a 'fabric first' principle (Camuffo, 2011). European standards (BSI, 2011) reinforce the point that thermal comfort is often in conflict with requirements for conservation and that compromise is often required.

In the UK, relatively few environmental heating studies have been carried out in churches. However, in a study of four churches in Cambridge, UK, four different heating strategies were evaluated through monitoring internal conditions at several locations. The results showed significant variation in the internal conditions measured in each church and that conditions were generally outside those required for both comfort and conservation where intermittent pew heating was installed, that constant conservation heating satisfied conditions required for conservation but not comfort of the occupants, and that constant central underfloor heating and central heating through water pipes offered both comfort and conservation conditions for the vast majority of the time. The overall conclusion of this study is that a heating strategy which combines constant ambient warm conditions at low temperature (12C – 15C), with localised heating introduced in those areas that are occupied should be developed (Makrodimitri et al, 2011). It is interesting to note that the church which had electric local heating in the pews was shown to be the most energy efficient of the four churches studied, although it was also established that this did not achieve satisfactory levels of thermal comfort (Makrodimitri et al, 2012).

The majority of European studies on heating systems and the environment in churches have taken place outside of the UK, both in temperate (Italy and Spain) and colder climate (Estonia, Poland and Scandinavia) zones.

Detailed environmental monitoring, over a three-year period, carried out in a church in Rocca Pietore, Italy, compared a traditional warm air heating system with a novel new system based on the principles of the Friendly Heating project. The new heating system provided small amounts of heat directly to people in the pew area while leaving the conditions in the main volume of the church undisturbed. The findings of this study, and others, led to the methodology adopted in a number of European draft standards (Camuffo et al, 2010).

In another study, carried out in the Giant Hall of a mediaeval palace in Padova, Italy, it was concluded that the intermittent heating of historical buildings results in a number of problems, which relate to heating system and strategy, the most important impact being significant fluctuations in temperature and relative humidity. The project recommended two innovative solutions, the first being to maintain constant internal temperatures during the cold season but compensate for the subsequent lowering of relative humidity, and the second being localised heating, which warms the people, not the room (Camuffo et al, 2004).

A study of a historic cathedral in Southern Italy demonstrated that the installation of an underfloor radiant heating system met the needs of thermal comfort for the church occupants and also provided optimal hygrothermal conditions for the preservation of various artefacts. It is acknowledged that the installation of this type of system is disruptive and expensive, but in this case the existing floor needed replacing anyway. The study highlighted that this type of system, being low temperature, is inherently energy efficient in the use of gas condensing boilers, but also has scope to be used with renewable energy systems including heat pumps and solar thermal collectors (Cardinale et al, 2014).

In a field study carried out at San Juan Bautista parish church in Madrid it was found that when the warm air heating system was on, there was significant stratification of environmental conditions, with heated zones being concentrated in the areas of the church 4.5m above the floor and comfort not being achieved in the occupied zone (Varas-Muriel et al, 2014).

A study of two churches in Poland, one constructed from timber, the other from brick and stone, showed that overhead radiant heating is capable of providing localised heating directly to the occupants of the churches, in order to provide comfort, without adversely affecting the integrity of painted walls and the works of art displayed (Samek et al, 2007).

In cold climates, the control of air movement, heating and moisture is often required. In a study carried out in a church in Harju Risti, Estonia, a cold climate, it was found that adaptive ventilation was appropriate when indoor humidity levels were high, that conservation heating with a heat pump was energy efficient for a significant proportion of the time, and that dehumidification was effective during the coldest periods (Napp and Kalamees, 2015). Other studies in cold climates have shown that conservation heating can be used to control relative humidity in order to conserve sensitive artefacts and that there is a significant potential for conserving energy by using heat pump technology and replacing thermostats with hygrostats. In this strategy, indoor relative humidity is controlled by heating the space to a point where the relative humidity is reduced to an acceptable level (Napp and Kalamees, 2015; Brostrom and Leijonhufvud, 2008).

2. The church buildings

This project was carried out to evaluate the environmental performance of three church buildings in Kent and West Sussex, in the UK, in order to evaluate heating strategy, environmental performance, energy consumption and carbon emissions. The three churches included St Bartholomew, Bobbing, Kent, St Peter and St Paul, Ashington, West Sussex, and St Mary, Washington, West Sussex. The two churches in West Sussex are very close to one another, being in the same parish, and the church in Kent is approximately eighty kilometres due North East from these two. A summary of the basic information for each of the three churches, including location and size data, is shown in Table 2. Environmental conditions of temperature and relative humidity were measured inside and outside the churches and energy consumption data was collected. Due to time, access requirements and resource limitations, the monitoring took place over a relatively short three-week period during the UK winter heating season. The period selected included three weekends, in order to test and compare the three churches when they were most fully occupied, as they generally are for Sunday worship services. This strategy allowed the impact of intermittent occupancy to be tested in order to evaluate the heating system and fabric responsiveness to be determined.

2.1 St Bartholomew, Bobbing, Kent

St Bartholomew Church in Bobbing is a Grade 1 listed building and is shown in Figure 2. The church has a rich and colourful history starting with a missionary established on the site in 670AD and with the church itself starting in the 13th Century. In later centuries the church was associated with King Henry III and King Henry IV who gave it to the monastery on nearby Isle of Sheppey. The church itself consists of two isles and two chancels and a tall spire.

The primary mode of heating at St Bartholomew is electric radiant wall heaters which are mounted at high level, above the pews, as shown in Figure 2. In addition to this there is an electric heat curtain system over the main door to the church, which gets switched off during services because of the noise. Occasionally, when the church is occupied for short periods of time during the week, such as for bell ringing, an electric fan heater and portable electric fire are used in the bell tower.

2.2 St Peter & St Paul, Ashington, West Sussex

St Peter and St Paul church is a grade 2* listed building and is shown in Figure 3. St. Peter and St. Paul dates from the 15th century, and was radically altered in 1871. Ashington originated as a chapelry of Washington but was created a parish in its own right around 1190. A chantry existed at Ashington Church in 1548. The church is of stone and flint with stone dressings and comprises chancel with north vestry, nave, south aisle and south porch. Before reconstruction in 1871 it had a short undivided nave and chancel with south porch, and a west bell turret with low shingled broach spire; the latter is recorded from the 16th century.

St Peter & St Paul church underwent significant improvements to the heating system in 2009, when the complete Victorian floor was removed and replaced with a dry installed system incorporating underfloor heating. The underfloor heating system is a wet system with two high efficiency gas fired condensing boilers, controlled via floor and room thermostats, with a set point temperature of 13°C, ensuring that the temperature in the church is kept above this temperature at all times, even when unoccupied. The system incorporates a layer of recycled foam glass, onto which is placed polystyrene panels with aluminium heat diffusers and pre-cut channels for the heating pipework to be positioned. Onto this a screed replacement tile is installed and then the natural stone floor slabs which are adhered using flexible adhesive. The floor is shown in Figure 3.

2.3 St Mary, Washington, West Sussex

St Mary church is a grade 2* listed building, a medieval church first built by the Knights Templar and is shown in Figure 4. After the addition of the tower in the 16th Century the church was re-ordered during the Victorian period. The church is faced in flint, with re-used Horsham roof-slabs above boarded roofs. Though wider than its predecessor, the north aisle keeps a lean-to roof, whereas the entirely new south aisle is gabled. The wall inside is arcaded, some arches containing lancets. The south arcade has hollow-chamfered arches and like the north one does not reach the west end.

St Mary Church had significant modernisation work carried out in 2012. The church needed a new kitchen and toilet facilities and a new heating system to replace the old and redundant gas fired wet system. New high efficiency gas fired boilers were installed, utilising some of the existing radiators, along with the addition of new free-standing radiators around the perimeter of the worship space. Down the nave and in the chancel, a trench heating system was installed with fin pipes with cast iron grills over to provide heat to the areas of the church unable to be heated with radiators. Elements of this new system are shown Figure 4.

3. Monitoring methodology

The primary aim of this study set out to evaluate the the performance of heating systems and controls, building fabric interaction, resource consumption and the impact of these factors on occupant comfort and the conservation of sensitive artefacts and materials. The primary objective was therefore to enable the optimisation of appropriate heating strategy in order to achieve this.

The environmental conditions and resource consumption in three churches were monitored for a three-week period, during the heating season, between the 7th and 27th January 2015. As mentioned previously, there were limitations to the period of monitoring, but this allowed monitoring to take place during three weekends; periods when all three of the churches were known to be occupied for regular congregational worship.

The environmental conditions inside and outside the churches were measured using self-contained, battery-powered devices which incorporate sensors for the measurement of temperature and relative humidity, and the ability to store this data over a significant period of time. For the sake of clarity, therefore, these devices will be referred to in this paper, as hygrothermal dataloggers.

There are a number of European standards that are relevant to the monitoring of environmental conditions in church buildings. The standard for indoor climate relating to churches (BSI, 2011) describes the importance of the impact of air exchange rates on indoor environmental conditions and energy consumption. It also sets out the requirement for establishing the *historic indoor climate*, which requires temperature and relative humidity to be monitored for a period of at least one year, or longer, if records are available. Given the scope and duration of this evaluation study, it was not possible to measure air permeability, or environmental conditions over such a long period.

Two further Standards deal with the procedures and instruments for measuring temperature and humidity in cultural property (BSI, 2010b, 2012). The impact of temperature is important and can have an effect on objects as they expand and contract with changing temperatures, the rate at which chemical reactions take place, the rate of bio-deterioration and the impact of temperature on relative humidity. Control of temperature is therefore important and reduces the risk of damage to objects and artefacts. The standard makes recommendations for procedures to be adopted in measuring both air temperatures and surface temperatures, acknowledging that some services are very sensitive to this. Since the heating strategies in the churches in this study include both radiant and convective heating, the hygrothermal dataloggers were located as far away as possible from heat sources, particularly convective emitters and direct radiant heaters. In this study, air temperatures were measured, rather than surface temperatures or mean radiant temperatures.

Environmental conditions of temperature and relative humidity, inside and outside of each church, were measured every 30 minutes, using a combination of HOBO H8 and LASCAR EL-USB-2 hygrothermal dataloggers. HOBO H8 dataloggers have an uncertainty (accuracy) of ±0.7°C at 21.0°C and ±5.0% RH. LASCAR EL_USB_2 dataloggers have an uncertainty (accuracy) of ±0.5°C at 21.0°C and ±3.0% RH. The HOBO dataloggers were used to measure external conditions and the LASCAR dataloggers where used inside the churches. The hygrothermal dataloggers are shown in Figure 5.

European standard EN15758:2010 (BSI, 2010b) specifies characteristics of temperature measuring instruments and those used inside the churches comply with the requirements of the standard, particularly in terms of range and uncertainty (accuracy). The external hygrothermal dataloggers had lower levels of accuracy but these were supported by additional data from third-party sources to corroborate the collected data. The impact of humidity on the conservation of objects and artefacts is critical and therefore its control is fundamental in conservation terms. Most materials are directly or indirectly affected by changes in humidity. Relative humidity has an impact on the rate of chemical reactions, and hygroscopic materials absorb and desorb moisture and, eventually reach an Equilibrium Moisture Content (EMC) with respect to surrounding temperatures and relative humidity. It is the variations in EMC that induces expansion and contraction in objects and high levels induce mould growth. Another European standard, EN16242:2012 (BSI, 2012), specifies the minimum requirements for humidity measuring instruments and defines these in terms of accuracy levels 1 to 4 representing very high, high, medium, and low. The internal data loggers used in this study comply with the accuracy level 3, Medium, which requires a level of uncertainty (accuracy) of 3% and those used to measure external conditions fall outside this range of uncertainty but as mentioned previously was supported by additional data from third-party sources. On a general note, those instruments specified as having very high and high levels of accuracy apply to chilled-mirror dew point metres and electronic psychrometers which were not available for this study and are often more appropriate for high accuracy single-point measurements rather than long term monitoring.

The internal environmental conditions were measured at two locations inside each church. At each of these two locations the conditions were also measured at various heights in order to evaluate vertical temperature stratification, critical in this project. Conditions were measured at heights of 0.5m, 2.0m, 3.0m and 4.0m above the finished floor level, by attaching the hygrothermal dataloggers to string lines and suspending them from high level. An image showing a typical string line, with hygrothermal dataloggers, in St Bartholomews, Bobbing, is shown in Figure 6. In addition, two hygrothermal dataloggers were placed outside each church in order to quantify external conditions measured simultaneously with those inside. The locations of the hygrothermal dataloggers at each church are shown in Figure 7.

Energy consumption data was collected at the start and the end of the monitoring period by taking energy meter readings and calculating the energy consumption during this period. These readings were converted to CO_2 emissions, using DEFRA published carbon conversion factors (Internet, 2015a), produced during the monitoring period and are shown in Table 3.

Representatives from each church were interviewed and provided detailed records relating to the heating cycles and occupancy patterns during this period. The periods when the heating system was operating, for each church, are shown in Table 4.

4. Results

The results for the data collected in the three churches are shown in a variety of different formats. Figure 8 shows a psychrometric chart indicating the average daily conditions of temperature, vapour pressure and humidity in the interior of all three churches.

It is clear from this that the average conditions in each of the three churches are very different, particularly in terms of temperature, with Bobbing being generally colder than Washington but with similar levels of relative humidity, and Ashington having higher temperature and lower relative humidities. The vapour pressures measured in Ashington and Washington are similar, whilst in Bobbing they are lower and of a greater range than the other two churches, suggesting that in Bobbing the moisture production rate inside the building is less, suggesting lower levels of occupancy. The data shows clearly that the relative humidity levels in the churches are significantly influenced by the average temperatures. Despite the fact that the vapour pressure in Ashington and Bobbing are very similar, the measured levels of relative humidity are significantly different; on average 20% lower in Ashington, primarily due to higher average temperatures but also due to higher levels of occupancy and a more continuous heating regime.

The temperature and relative humidity data for all three churches, Bobbing, Ashington and Washington, for the full monitoring period, is shown in Figures 9, 10 and 11 respectively. The data is presented for the measured conditions at each of the hygrothermal datalogger heights above floor level and also for the external conditions. For each of these figures, the top chart shows the measured data for temperature and the bottom chart for relative humidity. The data for each height represents the average conditions measured in the two internal locations at that height. The internal data for each church therefore gives some sense of stratification of conditions in each church.

Not surprisingly, the data in each church indicates where significant changes in environmental conditions take place and reflects the times during this period that the church was occupied. During these periods the temperature increases at the same time as the relative humidity reduces, reflecting the direct relationship between these two parameters. Each church responds to the occupancy and heating regimes in different ways, depending on the heating system specification, the thermal mass of the building, and the patterns of occupancy. For this reason, further analysis has been carried out, focusing on specific days when occupancy was known to be simultaneously relatively high in all three buildings. As a result of this, a direct comparison of the performance of each church has been enabled, for similar external climatic conditions, and this daily data is reported below.

4.1 Daily data

The data previously presented for the whole of the monitoring period, tells us a great deal about the environmental conditions in each church over a prolonged period of time in terms of occupancy and heating pattern. In order to focus on the responsiveness of the building fabric and systems, and on thermal stratification, it is essential to focus on specific days when there is known occupancy and heating patterns. In the case of these three church buildings, there were three Sundays when the churches were occupied by the congregation for normal Sunday service, where direct comparisons between the data can be made. The data being presented here was collected for the full 24 hour period of Sunday 11th January 2015 and Sunday 25th January 2015. Sunday 18th January was not included in this analysis because it was reported that the heating system at Washington malfunctioned, as can be seen clearly in the data collected at this location. This data is shown in Figure 12, and a direct comparison can be made between the three churches and their response to the heating regimes that are required to provide comfort conditions during the periods of occupancy. It is clear from the data that in order to provide occupant comfort conditions, the time at which the heating systems need to start warming the internal space is very different for each church, despite them having a similar volume and building fabric specification.

The radiant heating at Bobbing is relatively responsive, and provides comfort conditions quickly; however, after the heating is switched off, the church quickly returns to colder ambient conditions. In Ashington, with underfloor heating, inherent thermal mass, and a continual background temperature, the response is much slower and there is a relatively gradual increase in temperature over a much longer period of time; at the end of the heating period, the church cools down much more gradually than at Bobbing. The measured conditions in Washington show a system performance strategy that sits somewhere in between the strategies adopted at Bobbing and Washington.

Levels of heat stratification are also indicated in these results, with the largest variations in temperature measured across all heights at Washington, less so at Bobbing and less still at Ashington, which also reflects the heating regime in each of the three churches.

The average environmental conditions recorded on these two days have also been plotted onto two charts which show the measured internal conditions for each church and the broad environmental envelopes that provide human thermal comfort and conservation of sensitive artefacts (as shown previously in Figure 1). This is shown in Figure 13 and indicates that the conditions in all three churches rarely satisfy those identified as being required for occupant comfort. It could be concluded from this that the occupants would potentially be required to adapt their levels of clothing in order to satisfy their personal thermal comfort; something that is likely to have been the traditional approach to providing this comfort and also something that has been reported in the literature. Previous research has also shown that conditions are often outside those required for comfort and conservation (Makrodimitri et al 2012). The heating strategy that has been adopted at Ashington church is the only one that provides environmental conditions that are likely to preserve and conserve sensitive materials and artefacts.

It has been previously established that thermal stratification is a significant problem in many church buildings due to their large volumes, and the frequent use of heating strategies that warm up the air which then rises to areas that are unoccupied. The monitoring of conditions at different heights has allowed this issue to be addressed, and an analysis of the vertical stratification of temperatures has been carried out for both of these days, as shown in Figure 14. This data has been determined by comparing the difference between the minimum and maximum temperature, for each time step, and for each internal location in each church. The results show that there is significant variation in thermal stratification and that this is least at Bobbing, where the comfort of the occupants is provided by radiant heating, rather than heating the air itself; greater at Ashington, where the comfort is provided by underfloor heating, which is mostly radiant and partly convective; and highest at Washington, where the convective heating strategy warms large volumes of the air, which, through buoyancy, rises and caused significant thermal stratification.

5. Discussion of results

The three churches are similar in size and scale and are ancient buildings, primarily constructed using very dense stone materials which exhibit high levels of thermal inertia. As reported earlier in the literature, buildings of this type and age were not designed or built to incorporate heating systems and the systems installed to provide thermal comfort are very late additions to the buildings, within the context of the building life. The three churches were selected in this study because the heating systems and strategies are very different: Bobbing has electric radiant air heating, Ashington has a gas-fired water based underfloor heating system and Washington has a gas fired convective system installed. All three types of heating strategy are commonly found in churches across the UK, although the installation of underfloor heating is relatively new to the market, often involving high capital costs, and high levels of disruption during installation. These systems vary in terms of cost of installation, cost in use, energy and carbon efficiency, thermal responsiveness and ultimately in the comfort of the occupants.

The temperature and relative humidity data collected in the three churches during the whole of the monitoring period shows some interesting trends. The external temperatures measured at Bobbing and Washington are very similar, but those measured at Ashington are, on average, some 4°C lower. This is supported by the fact that there were two data loggers at each location and those at Ashington both indicated lower temperatures at this specific location, and was further corroborated by third party climatic data from the local Crawley Down Weather Station (internet, 2015b), which provided additional support that temperatures in this locality dropped to the levels measured. The external relative humidity data at all three locations are very similar.

The temperatures measured inside each church show clearly the periods of occupancy and heating cycles, with both Bobbing and Washington having peaks in internal temperatures which coincide with the occupancy data provided by the church representatives. In these two churches, it is clear that during unoccupied periods the temperatures remain relatively stable and a few degrees above the ambient external conditions. When the heating is switched on the temperatures rise, by between 7°C and 9°C, and when the heating is switched off the temperatures drop quickly to the ambient internal conditions. As has been reported in the literature, the greatest impact of environmental change is caused by such large fluctuations in temperature and relative humidity and can cause significant stress on the fabric of the building and artefacts inside. The response to the heating system is what would be expected for electric radiant and for convective air heating. In these two cases, and because of the limited occupancy in the building, the system either radiates immediate thermal comfort to the occupants (from a hot source), or warms the volume of air in the church (through convection), and very little interaction takes place between the internal environmental conditions and the thermal mass of the building fabric. The temperature measurements at Ashington are very different and it is more difficult to see from the data when the church is occupied. This is due to the fact that the system has been designed to keep the church constantly above a minimum set-point temperature, in this case around 13°C. This is clearly shown in the data that was collected between 21st and 24th January, when the church was unoccupied, and temperatures fluctuated between approximately 13°C and 15°C throughout this period. The strategy therefore relies on keeping the fabric (and thermal mass) of the building at a temperature well above the ambient conditions outside in winter, in order that when the church becomes occupied, the heating system has less work to do in order to bring the internal temperatures up to a comfortable level. Continuous heating has been identified in the literature as a favourable strategy that avoids the cyclical changes that can cause damage. The underfloor system in Ashington relies heavily on thermal mass and is therefore not a responsive one, but this strategy has led to an environment which is maintained constantly very close to thermal comfort conditions. The disadvantage of this is that the system uses relatively less energy to operate but for considerably longer, as is shown in the energy consumption and carbon emissions data presented earlier in the report. This data shows that Bobbing, Ashington and Washington produced 202 $kgCO_2$, 734 $kgCO_2$ and 287 $kgCO_2$ carbon emissions during the monitoring period, for occupancy periods of 15 hours, 47.5 hours and 33 hours, respectively.

At Ashington, the CO_2 and occupancy data in terms of occupancy and heating pattern, is complicated by the fact that the heating system is, in effect, constantly operating, maintaining the internal temperatures above 13°C. Further analysis of the collected data has been carried out to determine the number of hours that the heating system was operating, which has been assumed to be when temperatures are increasing from one time-step to the next, independent of what was happening outside. The results of this analysis are shown in Figure 15 and indicate that the heating patterns provided by the Ashington church representative significantly underestimate the overall period of time when the heating system is operating due to the fact that the conditions of the church are maintained at all times above the set-point temperature of 13°C. This modifies the results significantly, for Ashington church. The heating system was operating for 162.5 hours, rather than the 47.5 hours originally specified. The implications of this is that the carbon emissions results for Bobbing (electric radiant air), Ashington (gas radiant floor) and Washington (gas convective air) are **13.46** kg/CO_2/hour, **4.51** kg/CO_2/hour and **8.69** kg/CO_2/hour respectively.

The relative humidity data for all three churches generally reflects the trends of the temperature data, in that as temperatures rise internally, the relative humidity falls, as would be expected. However, the relative humidity in Bobbing and in Washington is high, on average, and this is likely to be primarily related to the generally cold internal temperatures during unoccupied periods. The relative humidity data collected inside Ashington tells a very different story, with levels being not only considerably lower than in the other two churches but also considerably lower than the simultaneous data collected outside the church. This can be explained by the heating strategy at Ashington, being one where the temperatures are maintained constantly above a set-point temperature, where because higher average internal temperatures are constantly maintained, the levels of relative humidity remain at a lower, healthier and more comfortable level. This might be particularly relevant where the deterioration of the building fabric is affected by high relative humidity levels, although temperature plays an important part in this issue too, as is reported in the literature previously.

The daily results also provide some interesting differences in the response of the heating systems, and fabric, of the three churches, and in the stratification of the temperatures measured. An energy efficient heating system is one that provides thermal comfort conditions to the areas occupied by the building occupants. In most buildings this is the occupied space between floor level and 2m above floor level. Church buildings are notoriously difficult to heat efficiently because warm air tends to rise to the upper parts of the building volume and significant stratification takes place. This causes high conduction losses and increased stack-effect ventilation losses at high level. One solution is the use of destratifying fans at high level to mix and move air around but these can be noisy (Bordass and Benrose 1996). Another is to use radiant heating systems, rather than air-warming heating systems, which provide thermal comfort conditions despite the air in the building being at a lower temperature. The results show very different responses to heating systems for the three churches monitored.

Ashington is the warmest church and maintains higher temperatures throughout the two days monitored. The response of the church is slower than at Bobbing and Washington, warming up more gradually and cooling down more gradually, demonstrating clearly the impact of the thermal mass of the system and the fabric of the building. In order for the church to reach comfort temperatures in the middle of the day, the heating system starts this gentle warming up process at 2am. Throughout the whole heating and cooling process there is very little stratification of temperatures at heights of 0.5m, 2.0m and 3.0m heights, and the temperatures measured at 4.0m are lower than those measured at the lower positions which suggests that thermal comfort is concentrated in the occupied height of the space, which indicates high levels of thermal efficiency.

Washington has a slightly faster response to the heating being switched on, and in order to ensure thermal comfort temperatures in the middle of the day, the heating switches on at around 3.30am. As temperatures climb in the church, the stratification at different heights is significant, and as much as 3°C between the maximum and minimum temperatures recorded. The literature has shown that in similar churches, where stratification occurs, the thermal comfort of the occupants is often not achieved as heat accumulates at high level. It has also been shown that these systems are known to cause severe stratification and there are consequences for doing so which include the negative impact that they have on the fabric and sensitive objects inside the church. The greatest temperature difference is between the data loggers at 0.5m and 3.0m and the temperatures measured at height of 4.0m are lower than at 3.0m, which is unexplained, although it is possible that this was caused by radiative effects on the sensors. The heating strategy in this church is one where the air is heated via convection and thus there is a very large volume of air to heat, and stratification of temperatures is more obvious.

Bobbing shows a significantly steeper temperature rise than the other two churches and suggests that the comfort of the occupants is achieved very quickly via electrical radiant heat exchangers. This is an inherently efficient way of heating large volume spaces that are occupied intermittently, but it also consumes a significant amount of electricity, which has a significantly larger CO_2 emission rate per kWh consumed than gas (and consequently is more expensive). The literature has shown that this type of localised heating is often installed in churches primarily for reasons of cost and because in an intermittently occupied building the energy is focused on where it is required for comfort, for a short period of time.

An analysis of the stratification of the temperatures measured in all three churches, on both 11th and 25th January, supports the hypothesis that stratification of temperatures in the vertical plane occurs least at Ashington (gas radiant floor), then Bobbing (electric radiant air) and are the highest at Washington (gas convective air).

6. Conclusions

It is appreciated that a study of this nature, over a three-week period, can serve only as an exploratory study and that further measurements over a longer period of time, preferably a full year, but at least over a full heating season, is desirable. However, despite the limited duration of the monitoring, the study has clearly demonstrated how the three churches, with different heating strategies, respond during periods of varied and intermittent occupancy, and a number of conclusions can be made.

Measured conditions show clearly the periods of occupation, and they are very different for each of the three churches. Bobbing is rarely occupied and really only heated for Sunday services, with some evening bell ringing; Washington is similar but has more regular services although there was clearly a failure in the heating system on Sunday 18th; Ashington is very regularly occupied by a variety of different groups throughout a typical week.

Bobbing and Washington are generally cold and only heated as and when required, whilst Ashington is maintained at a minimum temperature all of the time, with the temperature never going below 13°C during the whole of the monitoring period.

The data shows that the heating systems provide the thermal comfort conditions that they were designed to provide, but do so in very different ways. The responsiveness of the systems varies according to thermal mass issues and to heating strategy, the most responsive being electric radiant heating at Bobbing, followed by gas convective heating at Washington, followed by gas underfloor heating at Ashington.

As the literature review has shown very clearly, it is critical to recognise the importance of the balance between levels of occupancy in a church and the appropriateness of the heating system strategy. Ashington is a church which is very regularly occupied and has a heating system that constantly maintains temperatures above a set-point minimum. Bobbing and Washington are not regularly occupied and the heating systems are switched on and off only in order to provide comfort during intermittent periods of occupation. It can be argued that the systems that are currently installed in all three churches are appropriate for their levels of occupancy, but they wouldn't necessarily be appropriate if occupancy levels and patterns changed. It also follows that the levels of occupancy in any community church building might grow significantly if the environmental conditions in that building were more conducive to the occupants' thermal comfort. This is reflected in the overall levels of occupancy, and use, in the church at Ashington and the general feeling of well-being as one enters the building, even on a relatively cold day.

Because of the temperatures in these churches, the levels of relative humidity in Bobbing and Washington are generally high (cold) and in Ashington they are low (warm). In terms of the overall, long-term, average comfort conditions, therefore, they are good in Ashington (warm and dry) and not as good in Bobbing and Washington (cold and humid).

In terms of the energy consumed, and the carbon emissions produced, it is interesting to note that Ashington has consumed more energy, and produced more carbon emissions than Bobbing and Washington. However, this is fundamentally due to the fact that Ashington is occupied more of the time and that the heating system is often switched on outside hours of occupancy to maintain minimum background temperatures. Further evaluation and analysis of the data collected, using the periods when all three of the heating systems were operating, reveals that the carbon emissions produced, per hour of use were lowest in Ashington (gas radiant floor) at **4.51** kg/CO_2/hour; then Washington (gas convective air) at **8.69** kg/CO_2/hour; and highest at Bobbing (electric radiant air) at **13.46** kg/CO_2/hour.

In all three churches there is evidence of thermal stratification, and the results show that stratification of temperature in the vertical plane occurs least at Ashington, then Bobbing and is greatest at Washington. At Bobbing it is coolest at floor level and gets generally hotter as you increase in height; at Ashington it is clearly warmer at floor level (the level of the building that is occupied); at Washington it is coolest at floor level, and generally increasing with height.

The data that has been collected shows that the conditions in Ashington are the most favourable for comfort in terms of both temperature and humidity and that the heat being generated by the system is being most efficiently used in terms of stratification and heating the area of the building that is occupied. Ashington is also the church most likely to minimize the risks of damage to artefacts and the building fabric, and the most likely to satisfy conservation requirements.

A number of relevant general conclusions can be made:

- The environmental conditions measured in churches are very variable and are directly related to differences in a number of key parameters, including the heating system strategy and mode (radiation, convection, or a combination of the two); the level of heating system control; the continuous or intermittent use of the heating system and the regularity of occupation of the building by the community for a variety of uses.
- The most significant fluctuations in internal conditions of temperature and relative humidity, and those that are potentially most damaging, occur in intermittently heated churches with convective air heating systems compared to radiant and underfloor heating systems.
- Utilising the thermal mass of the building as part of the heating strategy can be beneficial for the comfort of the occupants, and the conservation of the building fabric and sensitive objects, particularly where the system maintains a background temperature higher than external ambient temperatures during the winter season.
- When evaluating the energy consumption and carbon emissions in any church building, the levels of occupancy must be taken into account in the metrics that are then used as benchmarks for good practice.

From an end-user perspective, the findings of this study can be broadly applied in any situation where patterns of occupancy and use of the building are changing, or where concerns about energy and carbon efficiency are appropriately considered as part of a longer-term strategy for building resilience in a changing cultural and physical environment.

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Figure captions

Table captions