Monitoring the thermal-hygrometric conditions induced by traditional heating systems in a historic Spanish church (XII-XVI C.).

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Abstract

Most historic churches are characterised by low thermal efficiency due primarily to their architectural design and the traditional materials used in their construction. Heating the huge volumes of air involved may be more or less effective depending on the HVAC system used. Up until very recently, traditional heating has been the system of choice in Spanish churches. The present study analysed the parish church at Talamanca de Jarama (a village on the outskirts of Madrid), where the forced hot-air system was found to induce wide fluctuations in indoor thermal-hygrometric (T/RH) conditions, in turn translating into the temporal and horizontal stratification of temperature and relative humidity. As a result, the thermal comfort sought for parishioners is not reached, for the air remains cold at pew height while heat accumulates in the upper area of the church. A three-dimensional sensor network was designed to monitor these conditions. Suspended from helium balloons, the sensors could record the indoor air temperature and humidity without causing any damage whatsoever to church property.

Keywords: church, traditional heating systems, thermal-hygrometric efficiency, monitoring strategy.

1. Introduction

Most churches in Europe are historic buildings that congregate large numbers of people for brief religious rites with fairly long intervals in between. The natural temperature, humidity and air

turbulence prevailing inside these buildings are determined primarily by the outdoor weather conditions, building structure and size, terrain hydrogeology and the construction materials used [1-3]. Since the high humidity and low temperatures found in most churches detract from occupant comfort, solutions aimed at indoor warming began to be sought in the twentieth century. These buildings were not originally designed or built for any manner of heating. Such systems were installed to temporarily heighten occupants' thermal comfort, to the detriment of the indoor conservation of the natural environmental conditions and churches' artistic and architectural heritage [4-14].

The heating systems most commonly installed were forced-air and hot-water radiators, in light of their low initial costs and the speed with which they can heat the large volumes of air inside churches. Moreover, they are centralised systems that may be used either continuously throughout the year to maintain constant indoor conditions or intermittently to improve overall thermal conditions for a short period of time [12-19].

Numerous studies have been conducted in recent years in some European countries in connection with the growing concern over the possible adverse consequences of the use of traditional heating. In countries with harsh climates (very cold, humid winters), expert opinion advised against their installation in churches because they induce wide fluctuations in the indoor environment and affect the conservation of church heritage [6, 8, 17]. New and better heating systems were designed and developed as an alternative. These systems, which include radiant floor and infrared radiation heating, thermal pews and electrical rugs and cushions, aim to raise the temperature locally in small areas without altering the overall indoor environment [8-9, 16, 20]. Recommendations and legislation on their installation and use have also been issued [18-19].

In Spain, churches first began to be heated in the nineteen sixties and seventies. In the absence of any regulation for this practice in such buildings until December 2012 (Spanish and European standard UNE-EN 15759-1: 2012), heating systems have been chosen in pursuit of occupants' thermal comfort, with no regard for the sustainable conservation of indoor church environments or the artistic heritage.

Most Spanish churches have centralised forced hot-air heating systems. This is the type of heating in place at San Juan Bautista Church (twelfth-sixteenth centuries) at Talamanca de Jarama, a town in the province of Madrid, Spain. The present study aimed to: a) design a working strategy to monitor indoor environmental conditions and their variations in the entire volume of air inside the church; b) assess the thermal-hygrometric efficiency attained with this type of heating; and c) determine how this system affects the indoor environment.

1.1. Description of the church and local climate

San Juan Bautista parish church (Figure 1), listed as a historic-artistic monument in 1931, is located at Talamanca de Jarama, in the centre of the Iberian Peninsula, 45 kilometres northwest of Madrid. The temple is characterised by a mix of architectural styles (Romanesque and Renaissance) and construction materials (dolostone ashlar and rubble, brick, clay, cladding and structural mortar, and Mudéjar wooden coffered ceilings). Its Romanesque (twelfth- to thirteenth-century) semi-circular apse and rectangular presbytery are built of dolostone ashlar. The main body of the church was rebuilt in Renaissance style in the sixteenth century using dolostone rubble, brick, clay and mortar. The rectangular floor plan (27 x 12.5 m) is divided into three aisles (a middle and two side aisles) separated by wide-span basket arches resting on large columns (both built with dolostone ashlar) that also support a wooden Mudéjar style coffered ceiling (Figure 2). By 1885, the south aisle and bell tower were near ruin and had to be rebuilt, at which time the choir was constructed over the south entrance.

The middle aisle is 10.5 m high and the side aisles and high altar (apse and presbytery) 9 m at their highest. The high altar is raised 90 cm over the floor in the middle aisle. Given those dimensions and its 393 m² footprint, the church contains 3952 m³ of air.

Talamanca de Jarama lies on the southern slope of the Guadarrama Mountains (Central Range) at an average elevation over sea level of 645 m. It is characterised by a semi-arid, continental

Mediterranean climate (cold winters and warm summers). In 1961-2003, the mean yearly temperature was 14 °C (Ministry of Agriculture and Environmental Affairs), although that mean rose in 2011-2012 (April 2011-April 2012) to 17 °C, with a 39 °C temperature range (40.2 °C in August 2011 to - 1.2 °C in February 2012). Rainfall is scant and variable (475 mm on average) and heaviest in autumn and spring. The yearly mean relative humidity (RH) is consequently only 48 % and the absolute humidity, 7 g/m³. Thermal inversions are a common occurrence, with fog induced by the town's proximity to the River Jarama.

1.2. Heating system

In 1972, the church installed a gas-oil-powered LIESCOTHERM OS/D-125 air heater with an output of 125 000 kcal/h, equipped with an automatic mechanical atomising burner. System autonomy is a mere 40 hours (15 l/h). This centralised forced hot-air system quickly heats incoming air from both outdoors (north side) and in (sacristy area, north side of the high altar) to a pre-selected temperature of 45 °C and blows, it into the church by convection. The rated hot-air flow is 9 m³/h.

The system is fitted with three blower vents at 3 m from the floor on the eastern half of the north wall (Figures 2 and 3). Two of these vents blow hot air toward the middle and side aisles, and the third toward the high altar. The return vent in the sacristy also works like a blower vent while the heat is on, directing hot air toward the high altar.

This facility was originally designed to ensure a minimum indoor temperature of + 15 °C at outdoor temperatures of down to - 3 °C. Thermal stability under those conditions was verified by the installers at 1.5 m from the floor and 2 m from the external walls.

The system is now used only intermittently, during religious services held in the coldest months, i.e., November to April. It is turned on four to five times a week (from Friday to Sunday) on average, for 1 to 1.5 hours.

2. Methodology

In this study, indoor temperature (T) and relative humidity (RH) were monitored before, during and after the heating was turned on for one hour. To monitor the entire indoor space, nine helium balloons were distributed at ceiling level (coffered wooden ceiling in the main body and dolostone ashlar over the high altar) at different points in the church (Figures 3 and 4). A band holding six to seven sensors (for a total of 56) spaced vertically at 1.5 m was attached to each balloon to measure thermal-hygrometric conditions at 1.5, 3, 4.5, 6, 7.5, 9 and 10.5 m.

Sensors were positioned at 10.5 m only in the middle aisle (He balloons B, E, G and I). In addition, seven sensors were positioned underneath the pews (40 cm off the floor) at approximately the same horizontal positions as the balloons to monitor the environmental conditions at floor level, where they would be perceived by the congregation (Figure 3).

The DS1923 i-Button T/RH button-type sensor/loggers used had an operating range for temperature (T) of - 20 to + 85 °C with 8-bit (± 0.5 °C) resolution, and for relative humidity (RH), 0 to 100 % with 8-bit (± 0.6 %) resolution. Readings were logged and downloaded with 1-Wire Wiewer x64 software.

Monitoring was conducted from 11:45 to 15:20 on two days, 29 February and 6 March 2012. Readings were taken every 60 seconds. The front of the church was monitored on 29 February (He balloons D, A, B, C and E) and the back on 6 March (He balloons F, G, H and I).

The outdoor environmental T and RH were measured at the same time with a 12-bit HOBO H8 ProSeries ONSET sensor, using BoxCar Pro-4 hardware for data logging and downloading. This sensor was positioned on the bell tower, facing south (Figure 3).

The airflow (m^3/h), velocity (m/s) and temperature (°C) of the hot air blown out of the vents were calculated with an AIRFLOW™ TA430 air velocity meter, with an operating range for air velocity of 0 to 30 m/s (precision = ± 0.01 m/s) and for temperature of - 18 to + 93 °C (precision = ± 0.1 °C).

The data logging and downloading software applied was LogDat2 Downloading.

3. Results

3.1. Natural environmental conditions prior to church heating.

On 29 February and 6 March 2012, the indoor and outdoor environmental conditions were monitored before the heating was turned on in the church. Monitoring lasted for 35 minutes (11:45–12:20) on both dates. The outdoor conditions, particularly relative humidity, differed on the two days (- 12 %, Table 1): both parameters exhibited lower values on 6 March. The differences in indoor mean temperature on the two days were insignificant, while the mean RH varied considerably (- 11-14 %, Table 1), with RH values up to 30 % lower on 6 March than on 29 February.

The outdoor mean T was similar to the indoor value (Table 1). In contrast, the outdoor mean RH was lower than the indoor value (≈ 10 %).

Although on 29/02 and 06/03 the indoor temperatures were similar and the RH values different, their behaviour and general pattern of variation, both horizontally and vertically speaking, were similar enough to justify correlation of the nine measuring points (Figure 5 and Table 2). Horizontally, the general mean T (11.1-12.4 °C) and RH (44.6-46.6 / 32.1-35.3 %) values were similar and uniform for the areas monitored by the sensors attached to the nine balloons (height > 1.5 m, Table 2). The horizontal range at < 1.5 m (Table 3) was similarly narrow but the T values were lower than at greater heights (10.1-11.7 °C), while the RH readings were somewhat higher (47.7-50.4 / 33.2-35.9 %). Vertically, the mean T and RH for each balloon (height > 1.5 m) barely varied, from 0.5 to 0.8 °C and 1.5 to 2 %. Greater thermal and RH variations (1.5 °C; 4 %) were observed in the high altar and choir only (He balloons D and I, Table 2). The highest mean T (12.6 and 12.8 °C) and lowest RH values were recorded in the high altar and choir (12.6 and 12.8 °C and 41.2 and 31.1 %, respectively), at 50-60 cm off the floor (Table 2).

Similar temperatures (Figure 5) were recorded in the north (A and F), middle (B and G) and south (C and H) aisles. The widest temperature range (i.e., the difference between the minimum and

maximum temperatures recorded by each sensor, ΔT) was detected in the high altar (D), centre of the middle aisle (E) and choir (I) ($\Delta T > 1\text{ }^{\circ}\text{C}$), and most prominently closest to the floor (50-60 cm), where $\Delta T > 4.6$ and $6\text{ }^{\circ}\text{C}$ (high altar and choir, respectively).

Excluding the choir (I) and the centre of the middle aisle (E), the T in all three aisles rose slightly with height up to 3 m off the floor (Figure 5, Table 2). At greater heights, the T values were flat or declined up to 6 m, where a second rise was recorded ($0.5\text{-}1\text{ }^{\circ}\text{C}$). In the high altar, the T began to rise ($0.5\text{ }^{\circ}\text{C}$) at a height of 4.5 m. Beginning at a height of 6 m in the high altar and 7.5 m in the other areas and up to the ceiling, T underwent another decline, except on the west side of the south aisle (H) and the choir (I), where it rose slightly. In both the choir and the high altar, temperatures slid steeply from floor level to a height of approximately 2-3 m, due to the effect of solar radiation warming on the floor materials (Figure 5).

The pattern of variation in relative humidity in the high altar and choir was inverted with respect to temperature. Where temperatures declined vertically, RH values rose (Figure 5, Table 2). The ranges RH values (ΔRH) also ranged widely, most intensely at 1.5 m from floors ($\Delta\text{RH} = 8.5$ and 10.5% , respectively), and stabilised at greater heights ($\Delta\text{RH} = 4\text{-}5\%$; Figure 5). RH variations concurred in the north aisle (A and F) and at the front (A, B and C) and rear (E, F, G and H) of the church (Figure 5). In the north aisle, RH declined slightly to just below ceiling level, and exhibited a minor rise at that level (Figure 5, Table 2). The ΔRH were small with scant vertical variations ($1\text{-}2\%$), except in F (west side), where the range RH values at 1.5 m was 4% . At the front of the church, RH tended to decline slightly with increasing height, although they rose near the ceiling, where the T was lower (Figure 5, Table 2) and exhibited a uniform ΔRH ($1\text{-}3\%$). At the rear of the church (except in F), RH tended to fluctuate, rising and declining slightly from one height to the next (Figure 5, Table 2). The ΔRH values were large and more variable than at the front of the church ($2\text{-}3\%$ for G and y H, and $3\text{-}4\%$ for E).

3.2. Conditions during operation of the heating system.

On the days when temperature, RH and air flows were monitored, the heating was turned on at 12:21 and off at 13:20, to simulate the normal 60-minute pattern of use in the winter months.

Hot air is blown into the church in different directions from the four vents, whose performance after the hour was observed to differ. The vent in the sacristy, located at a height of 2 m, blew 47 m³/h of airflow at a T of 50.5 °C toward the high altar at a velocity of 5.2 m/s. At a distance of 3 m from the vent in the direction of the altar stone, the temperature at a height of 2 m was 20.3 °C, and at 3 m, 21.5 °C (initial values, 10.6 and 11.1 °C, respectively). At an elevation of 3 m the airflow was 1.2 m³/h and moving at a velocity of 0.13 m/h.

Of the three vents located at 3 m on the east side of the north wall, the one on the right blows air toward the high altar; the one in the centre, toward the front of the middle aisle; and the one on the left toward the rear of the middle aisle (Figures 2 and 3). After operating for 1 hour, the vent on the right was generating a hot airflow of 40 m³/h, at a velocity of 5.4 m/s and a T of 52 °C. The airflow from the central vent was 51 m³/h, at a velocity of 5.6 m/s and a T of 50 °C. Hot air flowed from the left vent at 31 m³/h, a velocity of 3.5 m/s and a T of 46 °C. In other words, performance was lower in the left vent, which delivered a smaller flow at a lower velocity than the other two.

At a distance of 2.5 m from the right vent (in the middle aisle) and at a height of 3 m, the air T was 21 °C, with no significant air currents. At 2 m the T was 18.6 °C and at 1 m, it dropped to 15 °C. The initial T values at this distance and up to 3 m ranged from 10.6 to 11.6 °C.

At a distance of 2.5 m from the central vent (in the middle aisle) and a height of 3 m, the air T was 22.7 °C, with no significant air currents. At 2 m the T was 18.3 °C and at 1 m, 15.1 °C.

At 2.5 m from the left vent (in the middle aisle) and at the same height (3 m), the air T was 29 °C and significant air currents toward the rear of the middle aisle were detected. The airflow was 20.3 m³/h and its velocity was 2.3 m/s. These currents may have been induced by the air blown out

of the central vent. At 2 m, the T was 18.8 °C and at 1 m, it dropped to 15.1 °C. At these heights no significant air currents were present nor were any detected at 5 m from the vent at a height of 3 m.

Table 2 shows that during the 60 minutes (12:21-13:20) the heat was on, the mean T and RH values behaved and varied differently, both horizontally and vertically, from the natural values. Before the system was turned on, a mean T of ± 11 °C prevailed throughout the church, except in the SW corner (south aisle, H; choir, I; and middle aisle, G), where it was around ± 12 °C. After 60 minutes, east area in the north aisle (A, heat source area) and the central-eastern area (front of the church) in the middle aisle (B and E) exhibited clearly distinct behaviour, with mean temperatures of ≥ 18 °C. The next warmest area was the west part of the middle aisle (G and I), where the mean T values were 17-18 °C. The areas where heating was least effective (average T, 16 °C) were the high altar (D), south aisle (C and H) and west part of the north aisle (F). The mean RH values followed exactly the opposite pattern, with the lowest means recorded in the areas with the highest mean temperatures. In these areas (middle aisle and east side of the north aisle), the decline in RH entailed a mean loss of 25 % over the initial values.

By height, at 40 cm from the floor (Table 3), RH was not affected, while after 60 minutes the T, in turn, was only 1-2.5 °C higher ($+\Delta T$), climbing from 10.6-11.7 to 12.2-13.2 °C. The area where the sensation of warmth was somewhat greatest (≈ 13 °C) was close to the main heat source (NE corner of the church), while the coolest area (≈ 12 °C) was in the SW corner. In the high altar and choir, at 50-60 cm from the floor, the temperature range ($+\Delta T_1$) was larger (+ 3.5 °C) than in the preceding areas, with temperatures of 14.5 and 15 °C, respectively.

At a height of 1.5 m (at which, according to the technical specifications for the heating system, the mean T is 15 °C), the temperatures detected after 60 minutes of heating were ≈ 16 °C on the east end of the north aisle (A) and across the entire middle aisle (B, E and G), and ≈ 15 °C in the south aisle (C and H) and the west end of the north aisle (F) (Table 2). In the first area, the ΔT_1 (difference between T at 13:20, the end, and 12:20, the start of the heating period) fluctuated between + 4.5 and + 5.5 °C, and in the second, the rise was from + 3.5 to + 4 °C. Heating lowered

RH by $\pm 10\%$ ($-\Delta RH_1$) over the initial values, for a loss of humidity of from 15-20 % at the front of the church and 25-27 % at the rear (Table 2, Figure 6).

At slightly lower than 3 m off the floor, the temperatures rose steeply, by 7 to 8.5 °C ($+\Delta T_1$), while RH declined by ± 15 -16 % ($-\Delta RH_1$) with respect to the initial values. The peak T and trough RH values were recorded in the high altar (D), east side of the north aisle (A) and centre-west of the middle aisle (E and G). At that height, the high temperatures were around 18-19 °C (except in A, near the heat source, where $T > 20$ °C) and the RH dropped to 30-33 % (front) and 20-21 % (rear), for a humidity loss of 30-35 and 41-43 %, respectively, over the initial RH values (Table 2, Figure 6).

At 4.5 m in the east end of the north aisle (A), the temperatures rose substantially ($+\Delta T_1 = 17.5$ °C), to 28.6 °C, while RH declined to 17 % ($\Delta RH_1 = -30\%$, down by 63 % from the initial RH at that height), possibly because the sensor detected the hot-air flow from the vents located 1.5 m below at a distance of just 1.5 m (Figure 8). From that elevation upward, the T declined by 3 °C every 1.5 m, up to 7.5 m (22.6 °C). The rise in RH was not proportional to the decline in T, however, with values of 17.4 % (4.5 m) to 25.3 % (7.5 m) (Table 2, Figure 6a).

After 60 minutes, practically throughout the church, the highest T and lowest RH were recorded at heights of 4.5 to 7.5 m (Figure 8). The prevailing temperature at those heights was 21-22 °C ($+\Delta T_1 = 9$ -10 °C), while RH declined by 16 to 20 % ($-\Delta RH_1$), for a 40-50 % loss of the respective pre-heating RH. Temperature and RH followed the same pattern in the south aisle (C and H) and west side of the north aisle (F), where T values were on the order of 21 °C and RH slid by 16-18 % ($-\Delta RH_1$) (Table 2, Figure 6b). In the high altar (D), the temperature ranged from 20 to 21 °C, while RH dropped to 20 % ($-\Delta RH_1$), or to a level 42-43 % lower than the initial value. In the central-eastern area (B and E) of the middle aisle, the T was higher than in the west (G and I). At the front of the church (B and E), then, the effect of the direct flow of hot air from nearby vents raised the T at heights of 4.5-6 m to 21-22 °C, as in the rest of the church. At 7.5-9 m, however, the T rose to 23-24 °C, for a ΔT_1 of up to + 12 °C. Moreover, at 4.5-6 m, the RH dropped by 17 to 20 % ($-\Delta RH_1$),

down 35 to 45 % from the initial value, while at 7.5-9 m, the decline came to 22 % ($-\Delta RH_1$), for a 47-49 % loss of the initial RH at that height (Table 2, Figure 6c). Up to a height of 6 m in the rear of the church (G and I), the T was ± 21 °C ($\Delta T_1 = + 9$ °C) and rose to ± 22 °C ($\Delta T_1 = + 10$ °C) at 7.5-9 m. At 6 m, the RH slipped by 18 % ($-\Delta RH_1$) and at 7.5-9 m, by 19-20 % ($-\Delta RH_1$), down by 50 to 55 % from the initial RH at those heights (Table 2, Figure 6d).

In the 1.5 m immediately below the ceiling, in the aisles (9/10.5 m) and high altar (9 m), neither the T followed an upward pattern nor the RH a downward trend (Table 2). In these areas, the temperature was 1-3 °C lower than recorded by the sensor 1.5 m below (7.5/9 m), except in the choir (I) and the high altar (D), where it dipped by 4-5 °C. Consequently, the T prevailing in these high areas (19-20 °C) was similar to the values recorded at a height of 3-4.5 m (Table 2, Figures 6 and 8). At this height, in the front of the middle aisle (B and E), the temperatures were comparable to the values at 6 m (22 °C; Figure 6c). In the high altar area, the T near the ashlar stone ceiling was lower (16 °C) than the temperature recorded near the wooden ceiling over the aisles.

At these heights (9/10.5 m), RH rose by 2 to 4 % ($+\Delta RH$) over the values recorded at the same time at a height 1.5 m lower (9/7.5 m), but with respect to the initial values, it declined by 14 to 16 % ($-\Delta RH_1$), following the same pattern observed in other areas of the church. These declines and the resulting RH found in the south and north aisles (Table 2, Figures 6a-b and d) were similar to the values recorded at heights of 3 to 4.5 m. RH declined most in the warmest areas of the church (front of north (A) and middle (B and E) aisles) by up to 20-21 % ($-\Delta RH_1$) of the initial RH values, and these values concurred with the RH detected at a height of 6 m (Table 2, Figure 6c). In the high altar and the choir, where the T was lowest, RH rose by 11 and 9 %, respectively, over the values recorded at a height 1.5 m lower, and were down by only 9 and 13 % ($-\Delta RH_1$) from the initial RH (Table 2). In these two areas, the ceiling RH was higher than in any other part of the church.

Figure 6 shows that up to 1.5 m, the temperature rose and humidity declined slowly, reaching the peak and trough values, respectively, after the church was heated for 60 minutes. At higher levels,

by contrast, the temperature and RH varied more quickly, taking just 20 minutes to reach 80 % of their peak or trough values, respectively.

Figure 7 shows the relationship between T and RH at different heights after 60 minutes of heating. That this relationship is proportional and its linear regression equations are nearly straight lines ($R^2 \approx 1$) mean that the decline in RH depended directly on the rise in temperature and that this relationship was tighter at heights where the temperature rose most (4.5/9 m). By contrast, at low heights (< 1.5 m) in some areas of the church less affected by heating (such as the side aisles), measurements showed greater scatter and the linear regression equations were less straight ($R^2 < 1$). The inference is that in these areas RH was less impacted by rising temperature.

3.3. Post-heating conditions.

When the heating was turned off (13:21), the high temperatures declined quickly and the RH values climbed, likewise speedily, in the upper part of the church (4.5-7.5/9 m) (Figure 6). In contrast, at 3 m, the lag time for T decline was 5 minutes and during the 10-minute lag observed at 1.5 m, T even rose by 0.5 °C before heading downward. At 1.5 m, the rise in RH values also exhibited a 10-minute lag time. This was observed at the front of the church (Figures 6a-c) near the heat sources, while at the rear (Figure 6d), T was observed to continue to rise by +0.5 °C at the higher and +1 °C at the lower elevations: for 5 minutes at 4.5-7.5/9 m, 10 minutes at 3 m and up to 15 minutes at 1.5 m. Thereafter, the pattern was the same as at the front of the church, with swift declines in the upper air and more gradual lowering at <1.5 m. At the rear of the church, RH behaved analogously (Figure 6d). While the lag time for RH variations was 5 minutes in the higher areas where heat concentrated, this interval lengthened inversely with height, expanding to a total of 15 minutes at 1.5 m. Similarly, RH rose rapidly in the upper elevations and more slowly at the base of the church (Figure 6d). Post-heating thermal-hygrometric conditions stabilised to constant levels in 30 to 40 minutes (Figure 6). The reason for such speedy recovery is attributable to the heating

system itself, which cools the burner for 25-30 minutes after it is turned off by taking in cold, humid outdoor air, which then flows into the church through the four blower vents.

Table 2 compares the mean T and RH values before, during and after heating. Throughout the church, the post-heating (13:21-15:20) mean temperatures were 3 °C higher than the pre-heating means ($+\Delta T_1 \geq -\Delta T_2$). The mean RH values, by contrast, varied very little at the front of the church (A, B, C, D and E) and were somewhat lower ($\pm 6\%$; $-\Delta RH$) at the rear (F, G, H and I). During post-heating, the mean RH values at the rear of the church were closer to the means reached during heating, while at the front of the church they rose by $\pm 10\%$ ($+\Delta RH$). Relative to the mean T values reached during heating, the church cooled gradually from the east side of the north aisle (A - heat source) and central-eastern side of the middle aisle (B and E), where the mean temperature dropped by 4 °C, to the high altar (- 3 °C) and finally to the rear (F, G, H and I) and the east side of the south aisle (C), where the mean T was - 2 °C.

When the heating was turned off, the front of the church cooled more quickly and the RH rose more swiftly than at the rear, which cooled more gradually and RH values held steady longer.

Two hours after the heating was turned off the church, T tended to even out across its entire volume, both horizontally and vertically (small temperature differences). The peak T recorded at 15:20 in the church as a whole was around 12-14 °C (Figure 9). The lowest temperature (12-13 °C) was observed at all heights on the east side of the north aisle (A) and the high altar (D), and up to 3 m at the front of the church (B, C and E). The highest T (13-14 °C), in turn, was recorded at all vertical positions at the rear of the church (G, H and I) and above 3 m at the front of the building (Table 2, Figure 9).

By contrast, the pattern of RH variation differed depending on the day of the survey, although behaviour was consistently related to T patterns. At the heights where T dropped substantially ($-\Delta T_2 = 9-16\text{ °C}$), RH rose steeply ($+\Delta RH_2$), although the RH values were not clearly uniform either vertically or horizontally (Table 2). On 29/02, RH was high (48-52 %) at the lower levels at the front of the church (< 1.5 m) and declined inversely with height. In this area, RH recovered entirely

or even rose with respect to the pre-heating values ($+\Delta RH_2 \geq -\Delta RH_1$; Tables 2 and 3, Figures 9a and b). On 06/03, RH also declined inversely with height, with values of 33-34 % at < 1.5 m, but here $+\Delta RH_2 < -\Delta RH_1$, i.e., the pre-heating RH values were not fully recovered (Tables 2 and 3, Figures 9a-c).

At the same time, while the temperature dropped and humidity rose quickly at higher elevations, this behaviour was not observed near the ashlar stone and woodwork ceilings, where variations, particularly in T, took place more slowly. At these elevations, the T declined more gradually than in the rest of the church, maintaining values similar to or even greater than at lower elevations (14-15 °C at C, E, H and I; Table 2 and Figure 6). In contrast, RH rose quickly in these areas, with values somewhat higher than at lower levels, except in B and C (Table 2). In this stage, then, the areas immediately under the ceiling, 9-10.5 m in the middle aisle and 7.5-9 m in the rest of the building, were the warmest areas in the church (Figure 9).

4. Discussion

4.1. Natural environmental conditions prior to church heating.

The natural environmental conditions, RH in particular, inside the church during the measuring time slot (11:45-12:20) were heavily impacted by the outdoor conditions (Tables 1-3). Given the lack of natural ventilation in the church, no significant indoor air flows were detected.

The temperature barely varied during that 35-minute interval, either horizontally or vertically, with values of around 11-12 °C. The most significant rise in T (1-1.5 °C) was recorded in the areas affected by the solar radiation that beamed into the church through the windows around the high altar and choir and on the south wall. The warmest temperatures were found at floor level in the choir and high altar and at heights of 6-7.5 m in the middle and south aisles. The general tendency was for T to decline near the ceiling, as a result of the thermal inertia of the coffered woodwork.

Vertical and horizontal variations in RH were likewise insignificant across the church (with values of 44-46 % on 29/02 and 32-35 % on 06/03; Figure 5). The high altar and the choir (both built with dolostone ashlar) were the two areas where RH varied most, tending upward with height. The variations were smallest in the aisles (rubble and brick walls), with a slight rise in RH near the cold timber ceilings in the north aisle. RH varied somewhat more in the west end of the south aisle (an area with substantial capillary absorption induced by the solar radiation on the outer wall [21-22]).

Generally speaking, in the natural indoor conditions in the church prevailing between 11:45 and 12:20 on 29/02 and 06/03, the lowest T and highest RH values were recorded in the north aisle (A and F) and the highest T and lowest RH values in the south aisle (C and H), high altar (D) and choir (west side of the middle aisle - I). In short, while the differences in T (11-12 °C) and RH (44-46 and 32-35 %) were small inside the church, the thermal-hygrometric conditions exhibited some vertical stratification, with values that varied across the church from the east side of the north aisle (<T and >RH) to the SW corner of the south and middle aisles (>T and <RH).

4.2. Conditions during operation of the heating system.

The natural environmental conditions prevailing inside the building changed drastically after the heat was turned on (Figure 8). The greatest variation was detected in the upper part of the building, where in less than 20 minutes T and RH reached 80 % of their final (60-minute) values. In the convective dynamics generated, the jets of very hot air (45-50 °C) gushing at high speed (3.5-6 m/s) out of the vents in the east end of the north wall and the sacristy rose to heights of 4.5-6 m, converged at the east end of the central aisle (Figures 8a-b; 2.3-2.5 m/s, 22-24 °C), subsequently flowed to the rear of the church as a single tongue of hot air (21-22 °C) at heights of 6 to 9 m (Figures 8a-c) and ultimately splayed into the side aisles (20-21 °C).

At heights of over 9 m in the middle aisle and over 7.5 m in the side aisles and the high altar, temperatures waned to the values recorded at heights of 3 or 6 m (Figure 8). Temperature

attenuation in these areas near the ceiling may be the result of the physical condition (cooler and more humid) of the coffered woodwork ceilings in the aisles (19-20 °C) and the ashlar stone vault over the high altar (16 °C). At heights of under 4.5 m, temperature gradually declined by 3-4 °C throughout the church (Figure 8). The values recorded were, then, 21-22 °C at 4.5 m, 18-19 °C at 3 m, 15-16 °C at 1.5 m and 12-13 °C at 40 cm.

When the church was heated, variations in RH were closely related to variations in T (Figure 8). That correlation was even narrower at heights of > 3 m, where the steep rise in T (+ 7-12 °C) induced a likewise sharp rise in RH (40-50 % of the initial values). At heights of < 3 m, the decline in RH (15-30 %) was less impacted by the smaller rise in T (+ 2-6 °C, Figure 8).

T and RH distribution exhibited visible horizontal stratification in the heated church, with heat concentrating in the areas > 4.5 m off the floor (Figure 8).

4.3. Post-heating conditions.

Within 30-40 minutes after the heating was turned off, the substantial variations in indoor T and RH abated. The speedy decline in the high T reached in the upper areas went hand-in-hand with a similarly swift rise in RH. A several minute delay was recorded in the decline in T and hence in the rise in RH at heights < 3 m, however. Significantly, the front or head of the church, as well as the high altar and north aisle, cooled more rapidly than the rear and the south aisle. In the latter area, even after the system was turned off, the T continued to rise slightly for a few minutes, before following the same downward pattern as observed at the head of the church (steep decline in T at higher levels and a flatter decline near the floor). Here also, rises in RH were attendant upon the decline in T.

The exception to this rule was observed around the ceiling (timber coffering and dolostone ashlar vault) where it took some time for the T to drop after the heating was turned off because the delayed warming in these ceilings retarded the decline in the T in the surrounding area. Nonetheless, that

delay in T variations had no impact on the RH, which rose swiftly, an indication that the rise in RH was unrelated to the ongoing presence of high T in these areas.

The inference is that 30-40 minutes after the heating was turned off, nearly all the heat had dissipated, and after 2 hours the natural thermal-hygrometric conditions were fully restored (12-14 °C; Figure 6). Cooling began nearest the heat sources (NE and E) and continued from there to the S, SW and W areas of the church. In other words, the thermal-hygrometric conditions exhibited slanted vertical stratification at the front of the church, where cooling took place most swiftly, while at the rear, with more gradual cooling, stratification was horizontal. Also at the rear, the residual heat concentrated at higher elevations (Figure 9).

5. Conclusions

-The working strategy described in this article, i.e. a three-dimensional network of equally spaced sensors suspended from helium balloons, to monitor environmental conditions and their variations in the entire volume of air in the church studied is applicable to any type of building, regardless of its indoor dimensions, the season of the year or duration of the trials. Its use over longer periods would depend, however, on the quality of the helium filling the balloons and the possible inconvenience for building users. The number and type of sensors may also vary depending on the natural or artificial conditions to be measured. An added advantage of the method is that it causes no damage to building interiors, as no masonry is required to secure the sensors.

-The natural conditions prevailing in the wintertime inside San Juan Bautista Church at Talamanca de Jarama, Madrid, exhibited minor T and RH variations during the day. Temperature was more stable and uniform than RH, which depended on outdoor RH. Slight vertical stratification was observed in the thermal-hygrometric conditions, with T and RH values varying across the church from the coldest areas (northern aisle and high altar) to the warmest (south aisle and choir).

-When the forced hot air heating came on, the environmental conditions underwent horizontal stratification, with hot-air flowing (2.3-2.5 m/s) from the front of the middle aisle and from there to the side aisles, high altar and rear of the church at elevations of 4.5-9 m. This generated abrupt short-term disturbance in the natural conditions, as previously reported for central and northern European countries [2, 5-9, 15, 23].

-The temperature rose swiftly (to 21-24 °C in 20 min) at higher elevations, prompting a rapid decline in RH to 50 % of the initial values. In contrast, at the base of the church, to a height of 3 m, the maximum temperatures reached after 60 minutes of heating were 12-13 °C at 40 cm, 15-16 °C at 1.5 m and 18-19 °C at 3 m. These small (1-2 °C), gradual rises failed to reach comfort levels, since the thermal discomfort perceived at 40 cm from the floor was accentuated by the humidity values ($\approx$ 45-50 %) at these lower elevations, which were unaffected by the rise in T [4, 24-25]. While the 3-6-°C rise was perceptible at shoulder level (1.5-2 m), it did not attenuate the chill felt at lower levels. The most favourable floor level thermal conditions were observed around the altar stone and choir, where temperatures of 15-16 °C were recorded at 50-60 cm.

- The estimates of pew-level thermal comfort reported in this paper are based on the temperatures attained with the heating on, the complaints of some of the participants in religious services in the winter and a comparison to the values reported by other authors or recommended in codes and standards [4, 24-25]. Comfort indexes (PMV or PPD) have not yet been calculated, however.

-After the heating went off, the high T dropped and the low RH rose swiftly (30-40 minutes), both at the higher elevations and near the heat sources. This can be attributed to the system used to cool the burner, in which cold, moist outdoor air is vented into the church for 25 minutes through the four inlets at a rate of 3 to 4.1 m/s. Cooling was more gradual in the S, SW and W (south aisle and choir) of the church. Two hours after the heat went off, the initial environmental conditions were recovered nearly entirely and pre-heating vertical stratification was restored.

-Simply stated, the forced hot-air system in this building is scantily suitable, because it fails to reach the desired thermal comfort and efficiency. High T and low RH values concentrate in the upper part

of the church, while the environmental conditions (T and RH) sought for the occupied areas are not attained. Moreover, historic buildings are not designed to conserve this type of heat, in light of their low energy thermal efficiency. Expert opinion in the rest of Europe advises against the use of such scantily sustainable systems [5-6, 8-9, 18, 26]. If the system in the church at Talamanca de Jarama is not replaced, its efficiency could be improved if the humidity and moisture at the lower levels were eliminated and the system used to cool the burner overhauled to avoid the flow of cold, humid air into the church when the heating is turned off.

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TABLE AND FIGURE LEGENDS

Figure. 1. San Juan Bautista Church, Talamanca de Jarama, Madrid, Spain.

Figure. 2. Front of the church, showing the three hot-air blower vents on the left wall above the door to the heating room.

Figure. 3. Plan view showing the location of the sensors.

Figure. 4. Distribution of helium (He) balloons carrying i-Button sensor/loggers, spaced vertically at 1.5 m.

Table 1. Pre-heating environmental conditions inside and outside the church.

Figure. 5. Mean, maximum and minimum T and RH values at the nine indoor monitoring points: pre-heating vertical profiles.

Table 2. T and RH values before, during and after heating (height > 1.5 m).

Table 3. T and RH values before, during and after heating (40 cm off the floor).

Figure. 6. Thermal-hygrometric graphs during the monitoring period (11:45-15:20) for four representative areas.

Figure. 7. Scatter diagrams and regression lines for the two variables studied (T and RH) along the diagonal running from the heating system in the NE (A) to the SW corners (H) and crossing the centre of the church (E).

Figure. 8. T and RH distribution after 60 minutes of heating (13:20)

Figure. 9. Post-heating T and RH distribution (at 15:20, after two hours of no heat)