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Abstract

The impact of electric overhead radiant heaters on the microclimate, air flows, transport and deposition of suspended particulate matter (SPM) was monitored between March 2004 and March 2005 in the historic churches of Saint Michael Archangel in Szalowa and Saint Catherine in Cracow (Poland). The measurements show that although irradiation at the floor level increases temperature and reduces relative humidity in the interior of the church, the effect out of the heated zone and for the surfaces sheltered from irradiation is very limited, i.e. their extent is comparable with natural fluctuations inherent to the local climate of the church. The radiant heaters proved to generate little convectional flow of the air. Therefore, the heating system was not found to increase the concentration of SPM indoors; in particular, no re-suspension of particles already present in the church was observed. This work has demonstrated that the overhead radiant heaters are capable of providing localised heat to the areas where people congregate without adversely affecting painted walls and the works of arts displayed in churches. Care, however, should be taken that sensitive works of art are not exposed to the direct infrared radiation.

1. Introduction

Europe has a rich religious heritage with a unique legacy of art and architecture. Many historic churches contain valuable wall paintings, as well as liturgical and decorative objects. This religious architectural heritage has been deteriorating for many reasons; one of the most important is the adverse effects of an artificial climate produced by indoor heating during winter to satisfy modern demands for comfort. Historic churches were originally unheated, and some of them still are. However, the demand for heating by local communities has dramatically increased the number of churches which are heated for up to 5 months of the year. Different heating systems and regimes are used, the choice usually being made between warm air emitted from the floor or wall, radiant heaters – electrical or heated by gas combustion, water-filled radiators heated from a boiler, underfloor and pew heating [1–3]. Many of these, however, are planned for the comfort of the congregation without understanding conservation requirements.

Camuffo et al. [1] have recently extensively reviewed all aspects of church heating and the preservation of cultural heritage contained in historic churches. The review has documented serious destabilisation to natural indoor conditions introduced by heating that can cause problems in several areas: the physical integrity of works, the deposition of pollutants, the blackening of surfaces, the condensation of the excess of water vapour on cold surfaces. A stationary heating regime may bring the indoor temperature (T) to a high, ‘comfortable’ level causing a low and variable relative humidity (RH) indoors as the cold air outside is drawn in and heated up. The intermittent heating for liturgical services or cultural events may cause periodic fluctuations of RH corresponding to heating episodes when RH drops first from high to low levels and then returns to high RH after the heating system is switched off. In both cases, moisture-containing materials like wood, paintings on canvas, leather, textiles or paper respond to the variations in RH by absorbing or loosing moisture when the RH is high or low respectively. The moisture movement leads to the shrinkage or swelling of the materials [4]. Furthermore, it can cause cycles of salt dissolution and crystallisation in the surface layer of the walls threatening the adhesion of wall paintings [5].

Convectional air motions generated by sources of heat and temperature gradients between warm air and cold walls can much increase the rate of deposition of smoke and dust particles through aerodynamic capture, Brownian motions, thermo- and electrophoresis [6]. Interior sources of smoke can be incense and candles, also people bring in particles from the outside on their shoes and clothing. External gaseous and particulate pollutants can penetrate through the doors and windows, as well as other air gaps in the building envelope.

Observing the manifold degradation phenomena caused by heating has led many conservation authorities to conclude that no heating is the best option. However, the adverse effects can be considerably reduced if two general principles in church heating are respected:

- heating the church at a level that is as low as possible during the cold season, or carefully adjusting the heat input just to reduce the excessive dampness and the T drop in winter;
- providing localised heating to the areas where people congregate and maintain a natural or approximately natural climate in the remaining part of the church.

A broader European research programme ‘FRIENDLY HEATING’ was implemented to develop a novel heating system consisting of low-temperature radiant sources located in pews [7]. It was found that the system greatly improved the microclimatic conditions in the church interior by providing a localised comfortable temperature in the area where people congregate without changing the natural climate of the church as a whole [8].

Electric overhead radiant heaters that warm up the floor and seats, have been another system used to provide localised heat. There are generally two types of electric radiant heaters available:

- tubular heaters comprising an electric resistance wound around an isolating material, such as quartz glass which is heated to bright red temperature of 400–900 °C;
- halogen quartz lamps comprising a tungsten filament immersed in a halogen atmosphere in a transparent quartz tube which is heated to 1000–2400 °C.

If properly positioned, they are capable of rapidly warming people up, even those standing in areas where there are no or insufficient number of pews.

The aim of this project is to investigate in detail the effect of electric overhead radiators on the indoor environment of historic churches. The study focused on several key aspects: microclimate, air flows, as well as transport and deposition of suspended particulate matter (SPM). The ultimate objective of the study is to assess, and if possible to improve, the preservation conditions for the structures and the works of art.

It should be stated at this point that the authors did not attempt any broader study on the comfort level of the congregation. We relied on the subjective views of the users of the churches we investigated that they were satisfied with the heating systems and their usage patterns. However, it is known that the level of comfort depends on the homogeneity, intensity and symmetry of the IR radiation from the heaters [1]. Heads are heated more than feet and the combination of the overhead radiant heating with the pew heating is sometime adopted to improve the comfort. A further study is planned which will attempt to optimise the usage of the overhead radiant heating in churches and demonstrate the possibilities of balancing the human comfort and the conservation needs.

2. Experimental

2.1. Description of the churches studied

The primary monitoring site was the wooden church of St. Michael Archangel in Szalowa located at the fringe of the West Carpathians around 150 km south-east of Cracow, Poland (Fig. 1). A wooden church was selected for this study for several reasons. Wooden religious buildings are a unique legacy of art and architecture of high significance to Central, Eastern and Northern Europe. Furthermore, wooden churches are relatively open structures with fast air-exchange between indoors and outdoors and almost no capacity to store heat in the walls. Therefore, their indoor microclimate is particularly strongly governed by the fluctuating climatic conditions outside. On the other hand, paintings on wood and wooden decorative objects are particularly vulnerable to deterioration when exposed to lower levels of RH than the ideal in theory [9, 10], and than the RH to which the interiors were exposed in the past. As a result, any heating arrangement may have more adverse effects in a wooden church than in a brick or a stone church with a more airtight structure.

The church in Szalowa was built from 1736 to 1756, with the interior decoration completed around 1782. It is a construction of fir logs in the form of a basilica with the nave on the plan of an elongated rectangle, 10 m high, closed by a chancel. Two narrower rectangular side-aisles open into the nave through the arcades with arches supported on wooden posts. Ornate wooden decorations and furnishings preserved in the interior imitate in wood the monumental religious art of the late Baroque and Rococo period. They comprise wall paintings, paper wall hangings, a pulpit, wooden altars, portals, confession boxes, sculpted statues of saints, putti, vases and cartouches.

The existing heating system is installed for the winter period usually from November until March. It consists of radiant electric heaters mounted on the metal rods at a height of about 3.5 m above the floor level (Fig. 2). There are altogether eight rods in the nave and two rods in the chancel, heating the altar area. Each rod holds two radiant heaters of 2 kW power, which gives a total power of 40 kW during the church services. The rods with the heaters are bolted to the stone floor at the edge of the nave so that one radiator heats people sitting in the pews and the other provides heat to people standing in the aisles (Fig. 3). The heating is switched on around 10 min before the service and switched off after 45 min.

The monumental brick church of St. Catherine in Cracow was used as the second site, as it had a solid, more airtight building envelope hindering the air-exchange and offering better heat-buffering capacities. The church is a Gothic basilica, with three naves, built from 1365 to 1400. The heating system for the main nave consists of ten electric heaters mounted permanently at a height of 7 m above the floor (Fig. 4). Each heater comprises six radiant tubes of 2 kW, so the total operating power during services is 120 kW. Similarly to the church in Szalowa, the heating system operates for around 1 h during the service.

2.2. Monitoring of microclimate

The microclimate in the wooden church was monitored between March 2004 and March 2005. Therefore, both warm and cold periods were included. The monitoring system installed consisted of two battery-operated, programmable CR10-2M data acquisition units from Campbell Scientific, attached to five HygroclipS T-RH sensors from Rotronic. The measurements were performed every 15 min and the acquired data were recorded in the internal memory. To record short heating episodes the time interval for data acquisition was reduced to 5 min. The data was transmitted to the laboratory via Global System Mobile for Communications (GSM) using a Siemens TC35 module, and then evaluated. One sensor recorded the climate outdoors while several other sensors were deployed in the church. One was hung from the organ choir and monitored the air volume 5 m above the floor level irradiated by the heaters. This measurement was important to establish to what extent conditions in the upper, unheated part of the church, where many important wooden objects and sculptures were located, were disturbed by the heating episodes. An additional sensor monitored the conditions above an electric heater to record possible local effects of air warming when the heater was operated. Two sensors were placed at the floor level: one was exposed to the IR radiation from a heater, and the other was placed in the sheltered zone.

Monitoring in the church of St. Catherine in Cracow was limited to several periods during the winter of 2004/2005. The monitoring system used consisted of one data acquisition unit to which three T-RH sensors were attached. Similarly to the church in Szalowa, two sensors were placed in the heated area at floor level, one being exposed to the heating sources, the other hidden. The third sensor was deployed above the heated area on the pulpit 5 m above the floor level.

2.3. Monitoring methods for air flows and determination of ventilation rates

To monitor air flows in the churches, traces of sulphur hexafluoride (SF_6) gas were released from a cylinder in the middle of each church and a Brüel & Kjær Model 1302 Multi-gas monitor device, equipped with a six-channel sample-splitter, was used to monitor near simultaneously change in the SF_6 concentration at six diverse locations of each church. The monitoring points were located at least 1 m from the walls and 1 m from the floor of the church near two opposite corners of the nave, as well as in the chancel. They were also placed in the middle of the nave at three diverse heights (1 m, 3 m, and 6 m in Szalowa, and 1 m, 4.5 m, and 7 m in Cracow). The experiments were performed when the churches were heated or remained unheated, in order to study the impact of the heating systems on gas transport and the leakage of air into/out of the church. The ventilation rates were calculated from fittings to the decay parts of the SF_6 concentration curves.

2.4. Sampling of suspended particulate matter

Samples of SPM were collected in the indoor air of the church of Szalowa during March in 2004 and 2005, and of St. Catherine in Cracow in November, 2004 and February, 2005. The samples were taken at two locations: close to the altar, 1 m above the floor, and at the organ choir, approximately 5 m above the floor. Nuclepore filters of 0.4 µm pore-size and of 47 mm diameter were used within a Millipore filter-unit for the collection of bulk particulate matter. The unit was connected to a low-volume vacuum pump working at a flow-rate of about 40 l/min. Sampling time was approximately 24 h.

2.5. Bulk analysis of SPM samples

The filters were weighed before and after sampling to determine the mass of particulate matter deposited. Energy dispersive X-ray fluorescence (EDXRF) analysis of the samples collected in Szalowa was performed using a Tracor Spectrace 5000 EDXRF instrument equipped with a low power Rh-anode X-ray tube (17.5 W) to determine chemical composition of the bulk SPM samples. An accelerating voltage of 35 kV, a current of 0.35 mA and an acquisition time of 10,000 s were used for determining high-Z elements, while low-Z elements were determined at 10 kV, 0.35 mA and 4000 s, respectively. The measurements were carried out in vacuum conditions. The detection was performed by a nitrogen-cooled Si(Li) detector with a resolution of 160 eV at Mn Kα. The acquired X-ray spectra were de-convoluted with a non-linear least-squares fitting procedure (AXIL). The measured intensities were converted into elemental concentrations using sensitivity factors obtained from Micromatter Standards, Seattle, USA. In turn, the elemental bulk analysis of the samples from Cracow was carried out using a high-energy EDXRF Epsilon 5 instrument from PANalytical with a polarizing beam. It was equipped with a 600 W Gd-anode. Elements from Al to Ca were measured with a Ti secondary target and at an accelerating voltage of 35 kV and a current of 17 mA. Elements from Cr to Zn were measured with a Ge secondary target and at a voltage of 100 kV and a current of 6 mA. No filter was used. The measurements were carried out in vacuum conditions. The detection was performed with a nitrogen-cooled High Purity Ge-detector with a resolution of 165 eV at Mn Kα. The measuring time was 300 s per target. In the Epsilon 5 software package the complete sample quantification process was built in, going from acquiring the spectrum and the spectrum fitting over to the calibration and the quantification.

3. Results and discussion

3.1. Microclimate

To assess the destabilisation of the microclimatic conditions introduced by heating, it is important to know the local natural indoor climate to which the building and its content have adapted over their long-term exposure. A monitoring period between March and November in 2004 was selected as a reference, during which no heating system was operated. The microclimate in the wooden church in Szalowa is essentially governed by the fluctuating climatic conditions outside. A vigorous ingress of outside air into the interior is possible through the relatively open wooden structure and doors. The natural ventilation rate in the church, when the heating was off, was around 3 air changes per hour (ACH), which can be regarded as an extremely high air-exchange rate (AER). For example, AERs of around 0.1 is typical of churches with airtight plastered stone vaults and AERs of 0.5–0.75 for churches with wooden vaults [2]. A high AER between indoors and outdoors is illustrated in Fig. 5 by plots of the corresponding internal and external moisture contents in 2004, expressed as the humidity mixing ratio (MR), i.e. grams of water vapour per kilogramme of dry air. The MR inside increased from about 3 g/kg in March to 13 g/kg in August, which was in accordance with the external seasonal variations. The MR values indoors were consistently higher than outdoors, which pointed to internal sources of extra moisture in the church, people visiting the church being the most important. Fig. 6 shows plots of T and RH inside and outside the church for the same period. The interior T increased from a minimum value of 0 °C in March to 25 °C in August and September. RH did not show any distinct seasonal variation and fluctuated irregularly around an average of 70%. The outside climatic variations were smoothed inside due to buffering by wood. The buffering effect of wood is particularly evident when short time variations are analysed (Fig. 7). During June 2004, the daily variations of T and RH could be up to 5 °C and 14%, respectively when compared to the values of 24 °C and 80% outdoors. The diurnal cycles in RH were thus particularly effectively buffered by the cyclic release and absorption of moisture by the wood. The capacity of wood to release moisture could be exhausted, as exemplified by a dry period in March 2004 when the RH level moved gradually from 75 to 45%, the lowest RH value recorded in the church for the monitoring period (Fig. 8).

Measurements made during the winter 2004/2005 period provided direct information on the disturbance of the microclimatic conditions introduced by indoor heating. Fig. 9 shows characteristic short-term variations introduced by several heating episodes recorded during

December 2004 when the church was frequently used for services. As expected, the T of the irradiated surface rose by around 13 °C, when the heating was on, and the RH in the air layer in contact with this surface dropped by more than 20%. The changes in T and RH were considerably smaller in the zone which was not irradiated, i.e. 7 °C and 9% respectively. The RH variations were smaller than one would expect from the T changes as they were compensated for by the release of moisture by the materials irradiated. The release is clearly visible in Fig. 10 which shows variability of the indoor MR during heating.

The observations clearly indicate that though irradiation of the congregation area at the floor level increases T and reduces RH throughout the entire church, the effect outside the heated zone and for the surfaces sheltered from irradiation is very limited, comparable to natural fluctuations inherent to the local climate of the church, for example caused by the diurnal cycle of T and RH during the warm months of the year. High natural ventilation rate of 3 ACH, observed in the church, contributed to the reduction of the indoor accumulation of heat via leakage and thus prevented larger drop in RH.

The large Gothic brick structure of the church of St. Catherine has a far lower natural ventilation rate of 0.2 ACH but a greater capacity to accumulate heat. In spite of the different construction and location of heat sources, characteristics of the short-term variations in microclimatic parameters introduced by heating episodes proved remarkably similar to those described for the wooden church of Szalowa, so they would not be quoted in detail. This additional monitoring further reinforced the conclusion that the effect of the electric overhead radiators on the general microclimate of the church outside the heated zone was limited.

3.2. Air flows and ventilation rates

The evolution of the concentration profiles of SF_6 tracer showed similar, exponential decay for each measurement point in the wooden church. However, the absolute values of SF_6 level were different at the six locations since it was not possible to reach a uniform distribution of the tracer gas in the church because of its fast removal from the open wooden structure. The ventilation rates were very high, 2.7 and 2.9 ACH, for the idle and the working heating system, respectively. This negligibly low influence of heating on the ventilation rate was due to the fast air exchange of the building as indicated above.

The ventilation rate for the large brick church in Cracow was much lower; 0.17 ACH. For this church, a fast and complete mixing of the released SF_6 was observed. The heating promoted both a faster transport of air within the church and a faster removal of the gas from the church, as shown in Fig. 11, the calculated ventilation rate being 0.27 ACH. This value is in accordance with previous observations on the stone church of Rocca Pietore [11].

3.3. Transport and deposition of suspended particulate matter

The measurements were principally aimed at establishing whether the heating system, when operating, increased the concentration of particulate matter in the air either by increasing its infiltration from outdoors or by re-suspending particles already present in the church. The samplings were carried out, therefore, always according to the same pattern: on one day the indoor air was sampled in several locations in an unheated church, on the next day the same sampling was done in the heated church. The samplings in the heated churches were carried out both on ordinary days when the buildings were empty and on Sundays when the church was visited by a large number of people attending several services. In such a way, pairs of values of the particulate contents in the air were obtained for the adjacent days with and without heating, which reduced to some extent the possible influence of the natural variation in the particulate content inside the church for example due to the changes outdoors. Ratios of the indoor particulate contents during heating to that in the absence of heating in the adjacent days were calculated for each sampling point and the values obtained are shown in Fig. 12, separately for empty churches and churches on Sundays with high attendance of the congregation for services. The average values were 0.8 ± 0.2 for empty churches and 1.2 ± 0.4 for churches used on Sundays; the uncertainties are standard deviations of the mean values. It is clear that within the standard deviation the heating system does not increase the amounts of SPM in the indoor air. A slight increase in the ratio of particulate content on Sundays when compared to the unheated empty church is obviously due to the intense use of the church when external particles are brought in or particles present in the interior are re-suspended by people.

Using EDXRF, twelve elements were quantitatively determined. Seven of the measured elements were present at significant concentrations, making up 93–97% of the total. They comprised Al, Si, S, Cl, K, Ca, and Fe. Their concentrations in SPM are listed in Table 1. As one can see, these elements represent no more than 20% of the total weight of the particulate present, usually between 5 and 10%. The remaining, major part of SPM is built up by light elements like carbon, oxygen or nitrogen, not detected by the XRF analysis. There are marked differences between the contents of elements detected in various samples. In both churches, sulphur is the dominating element. For many samples it shows levels several times greater than other elements detected. The Al, Si and Fe show high relative levels in the particles collected in the wooden church of Szalowa located in a rural area. The elements are thought to come from soil dust, generally of large particle size, brought in by the visitors. The concentrations of soil particles in the indoor air are much higher at the floor level, which is consistent with their large size. The soil dust is almost absent in the indoor air in the urban church of St. Catherine, which in turn contains a higher amount of Cl, an element coming from the salt used to de-ice streets.

Generally, there were no marked and systematic differences between the relative elemental contents of particulates collected during heating and in the absence of heating. The exception was higher sulphur content in samples collected in the rural wooden church on days with no heating when compared to those collected on days when the heating was operated. It should be noticed, however, that the absolute total particulate levels on the day with the heating operating were much lower. The analysis of single particles revealed that sulphur was predominantly present as fine particles of ammonium sulphate. If one assumes that the atmospheric concentration of ammonium sulphate was approximately stable in the area where measurements were done, similar amounts of the compound must have been collected during sampling. With the total particulate content decreasing, these would show as a relative increase in the sulphur content.

4. Conclusions

The results of the present study add new information on the use of overhead electric radiant heaters in historic churches. Warnings have been issued that the sensitive works of art, responding rapidly to changes in T and RH, like paintings on canvas or wood panels, exposed to intense infrared radiation can be damaged by the direct increase of the temperature and by the associated loss of moisture [1]. Therefore, the overhead electric heaters should be properly positioned to avoid irradiating sensitive objects. An annoying glare, when they operated, was a problem in the past. Heaters more recently produced have much improved, visibly neutral spectral characteristics. Some disadvantage can be a negative visual impact of the radiators mounted in the historic interiors. Further work on the sources better adapted to the needs of the conservation sector is necessary. However, the present work has demonstrated that they can provide localised heat without adversely affecting walls and the cultural heritage contained in churches: their effect on the general microclimate outside the heated zone is limited, they generate limited convective movement of the air and, as a result, little re-suspension and transport of particles.

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Table 1
Concentrations of seven elements in SPM which were abundant among those detected by the XRF analysis

Site	Sampling level	Heating	Total SPM [μg m^{-3}]	Contents of elements in the total SPM [%]							
				Al	Si	S	Cl	K	Ca	Fe	Total of these elements
Rural Szalowa	Floor	Heated	19	1,3	3,1	8,6	0,3	1,5	2,3	1,5	18,6
		Unheated	37	1,5	4,0	4,1	0,6	1,3	2,0	1,4	14,9
	Organ choir	Heated	34	0,4	0,9	5,9	0,1	0,8	0,5	0,6	9,2
		Unheated	42	0,6	1,2	4,8	0,7	1,1	0,6	0,7	9,7
Urban Cracow	Floor	Heated	38	0,1	0,3	3,6	0,7	1,0	0,4	0,3	6,4
		Unheated	40	0,1	0,3	3,6	1,2	1,7	0,3	0,7	7,9
	Organ choir	Heated	31	0,1	0,3	4,1	1,0	1,2	0,5	0,3	7,5
		Unheated	43	0,1	0,3	3,8	2,3	1,8	0,3	0,7	9,3

Fig. 1. Wooden church of St. Michael Archangel in Szalowa, Poland, 1736 - 1756.

Fig. 2. Wooden church of St. Michael Archangel in Szalowa, Poland. View of the interior with overhead radiant electric heaters operating.

Fig. 3. Details of mounting the heaters on the metal rods at the height of about 3.5 m above the floor.

Fig. 4. Main nave of church of St. Catherine in Cracow, Poland, 1365e1400. Electric heaters, comprising six radiant tubes each, are mounted permanently at a height of 7 m above the floor.

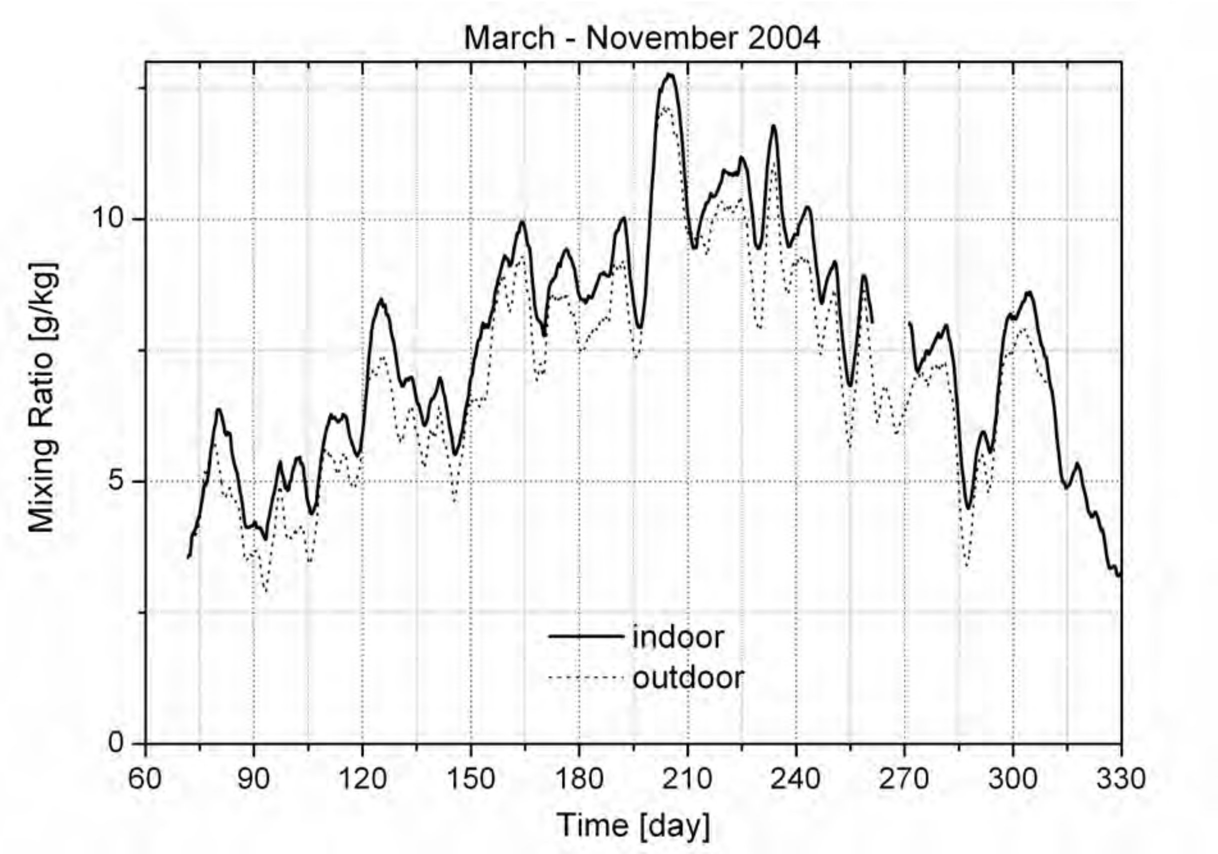

Fig. 5. Indoor and outdoor moisture contents between March and November 2004 expressed as humidity mixing ratio (MR). The plots were smoothed by calculating an average of the data points every five minutes in the two adjacent 24 h periods.

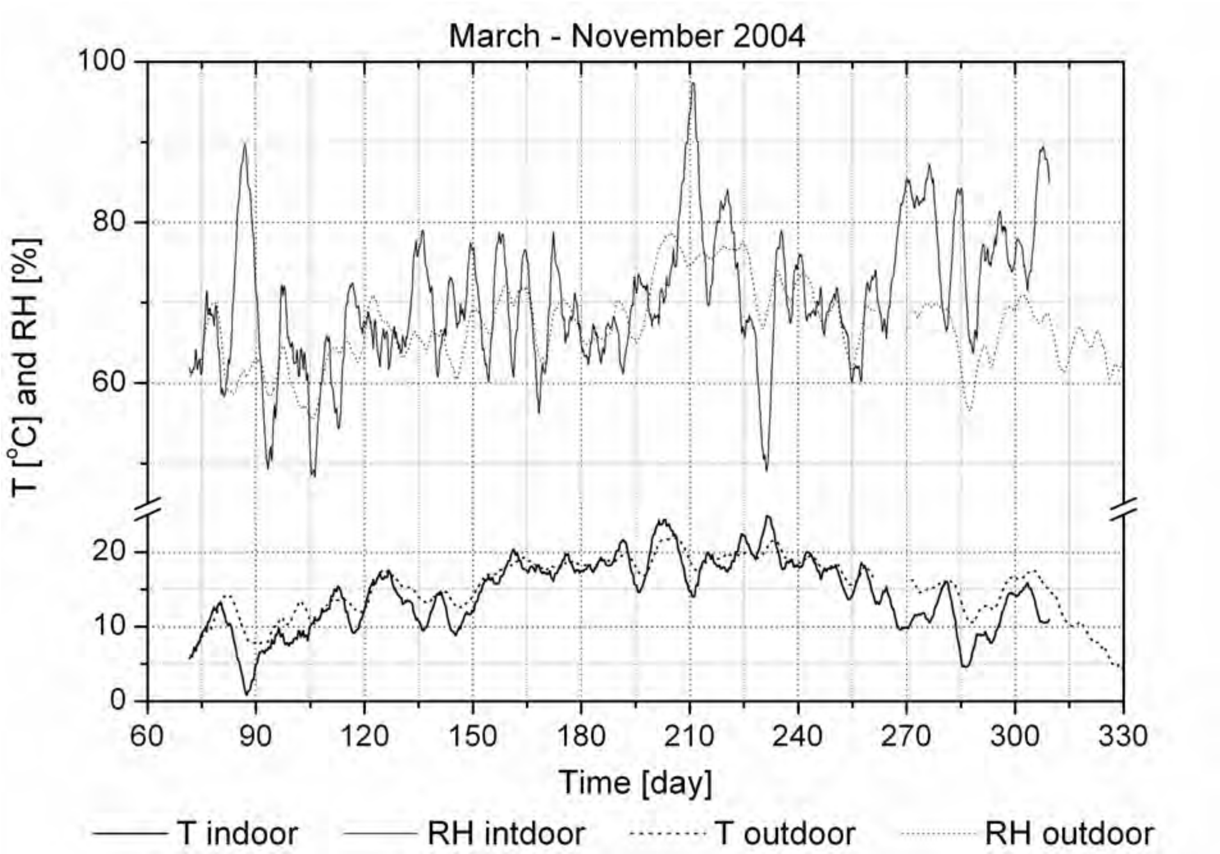

Fig. 6. Indoor and outdoor climates between March and November 2004 as plots of T and RH smoothed as in Fig. 5.

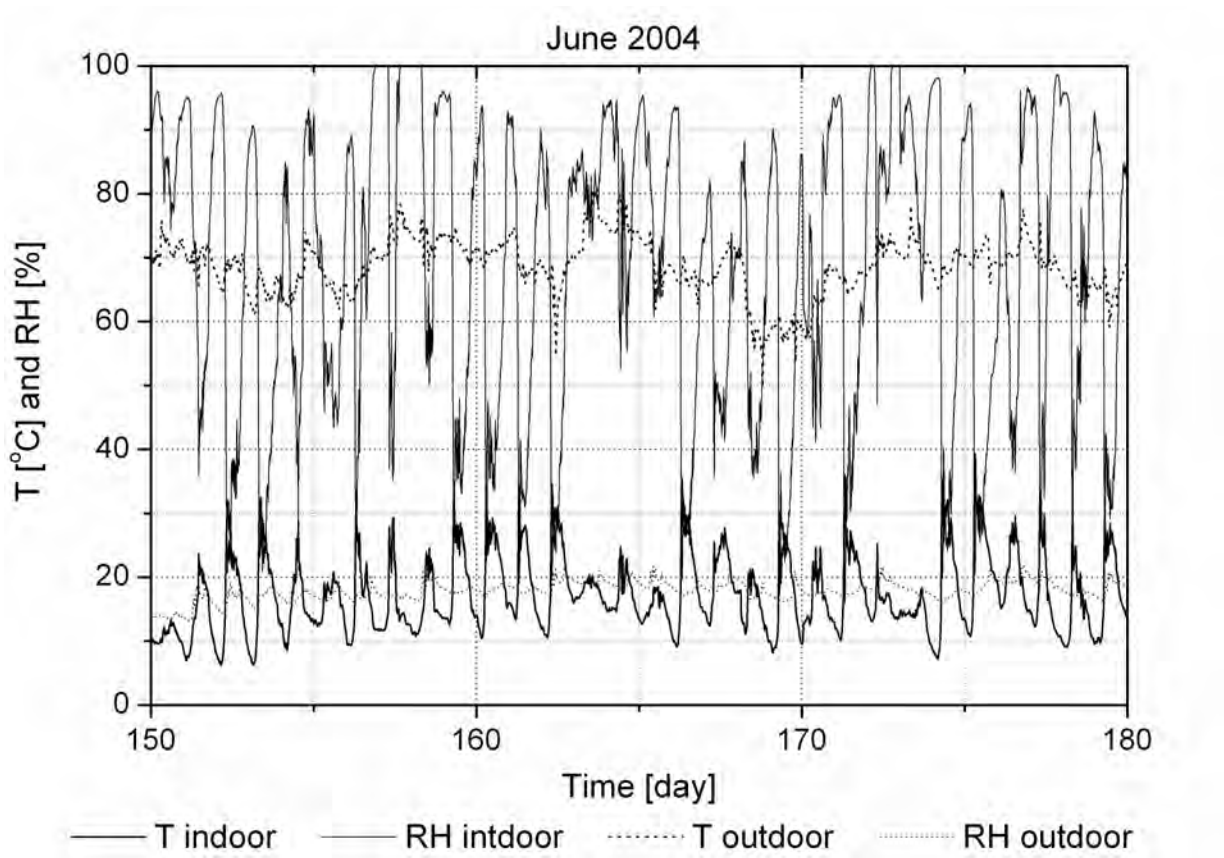

Fig. 7. Indoor and outdoor climate in June 2004 as plots of five-minute values of T and RH.

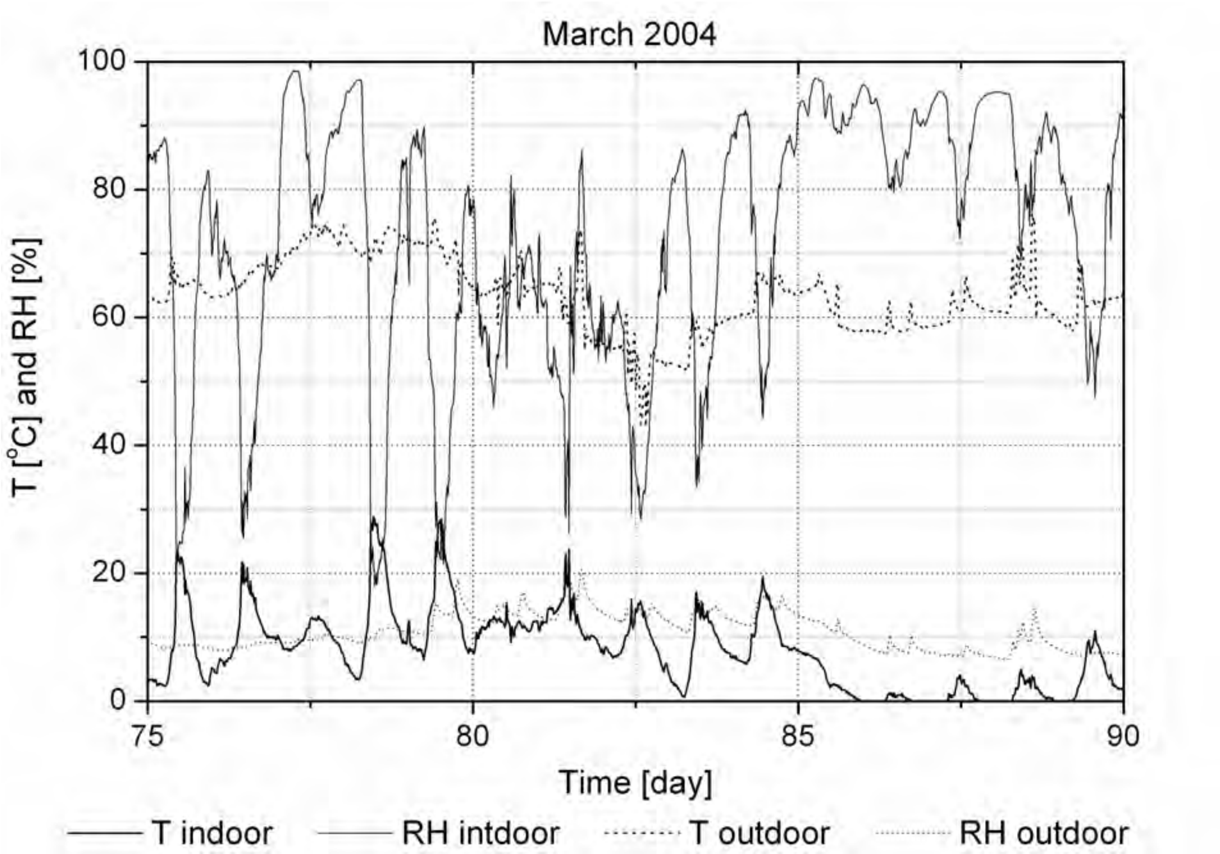

Fig. 8. Indoor and outdoor climates in March 2004 as plots of five-minute values of T and RH.

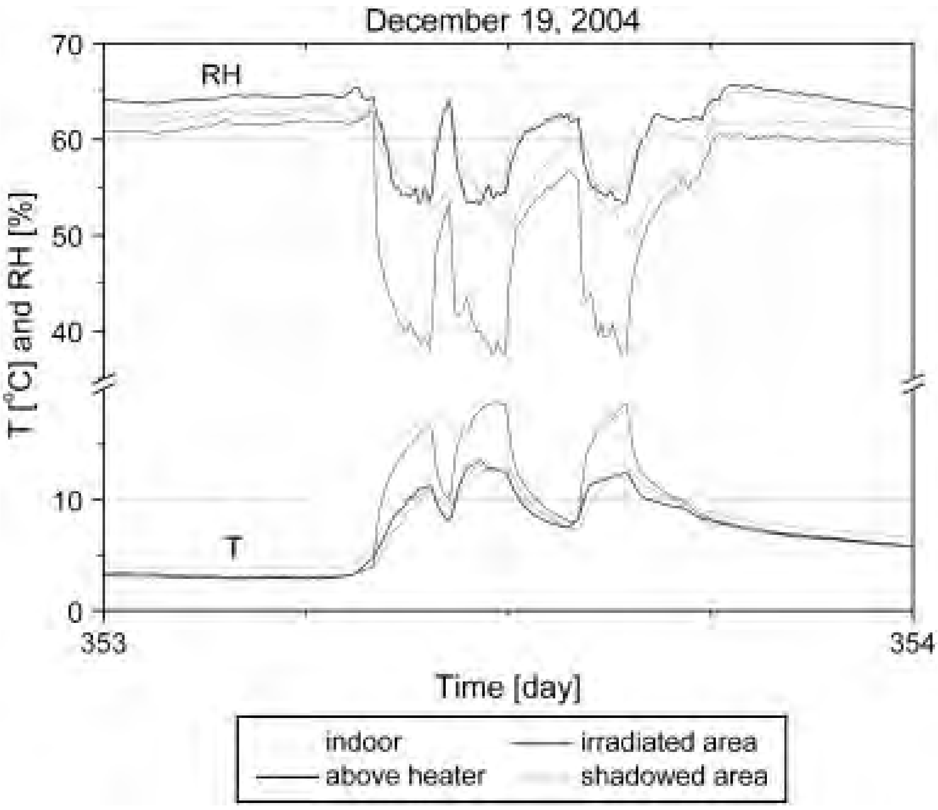

Fig. 9. Short-term variations in T and RH due to heating episodes on December 19, 2004 recorded at several locations in the church.

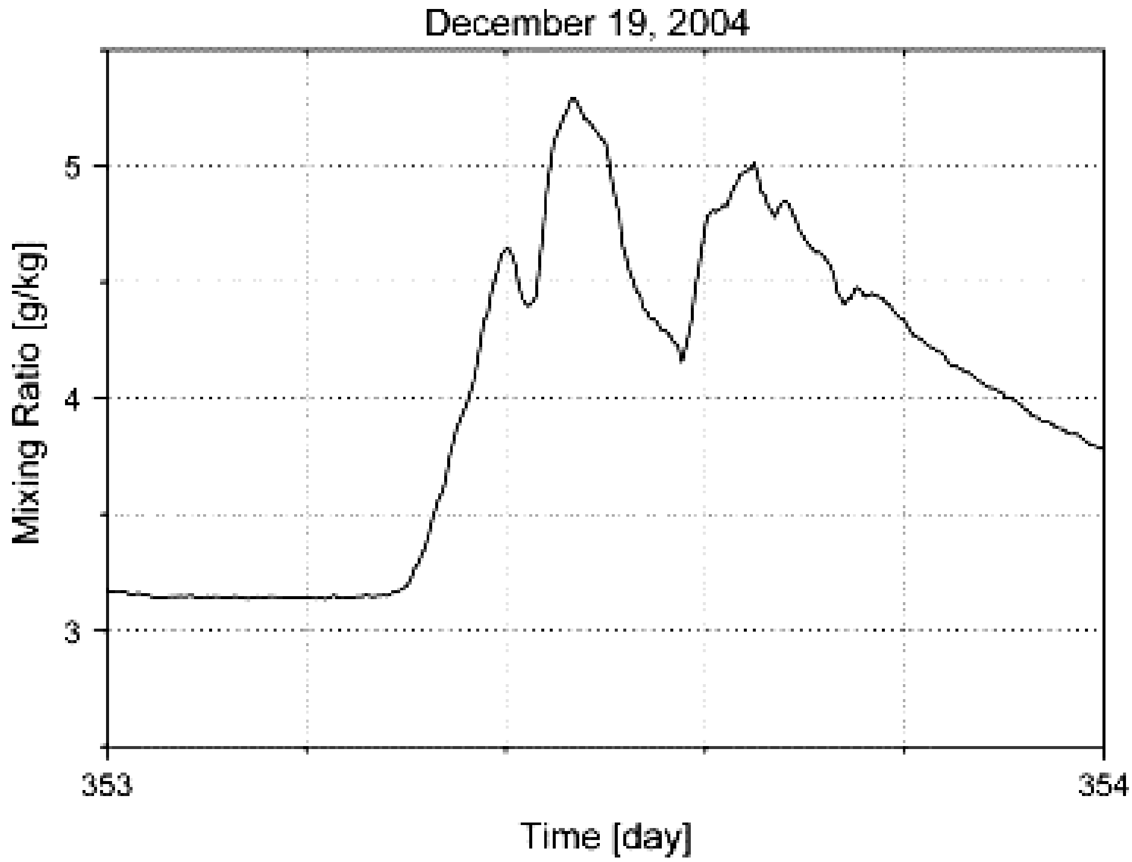

Fig. 10. Variation in the indoor moisture content expressed as humidity mixing ratio (MR) due to the heating episodes analysed in Fig.9.

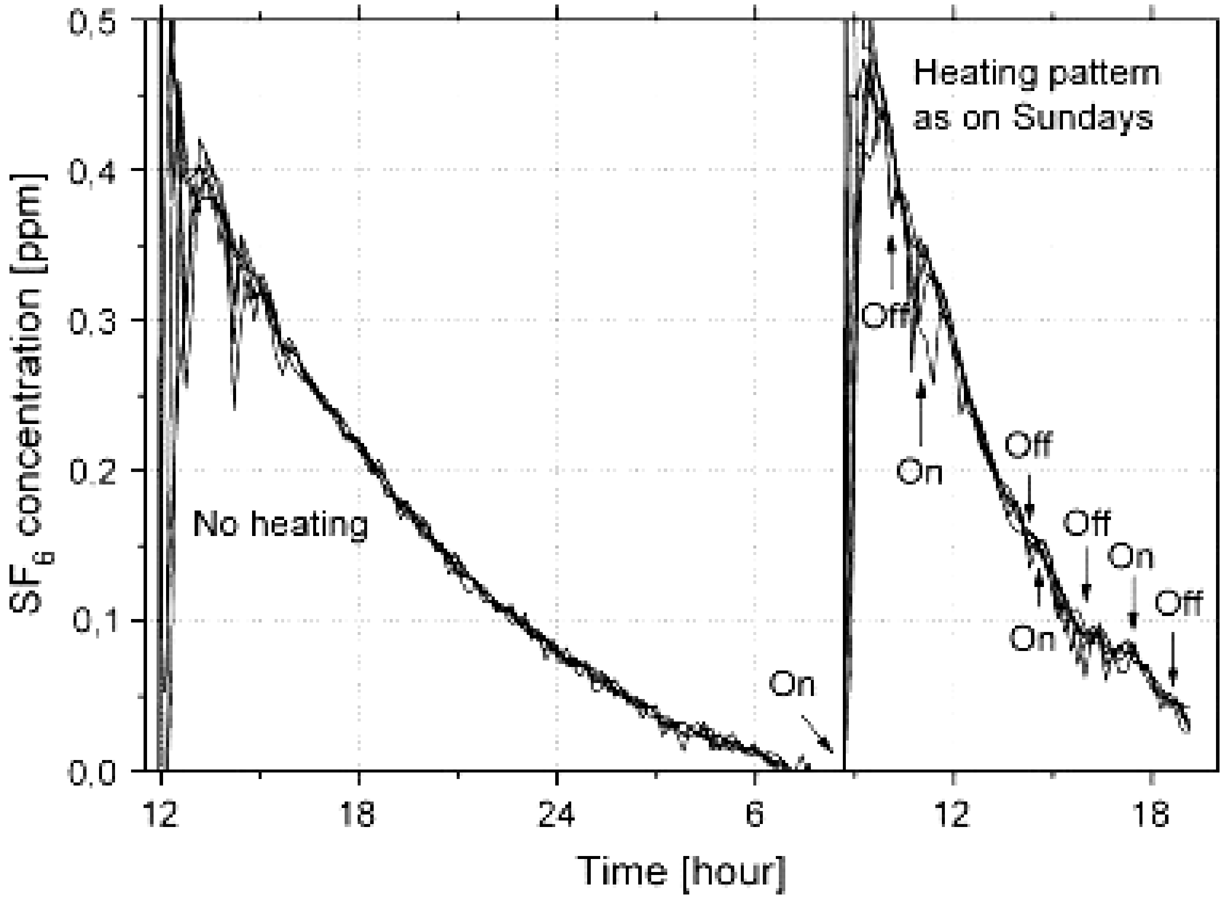

Fig. 11. Evolution of the concentration profiles of SF_6 tracer at six measurement points in the church of St Catherine in Cracow, first unheated, and then heated following the pattern of use on Sundays.

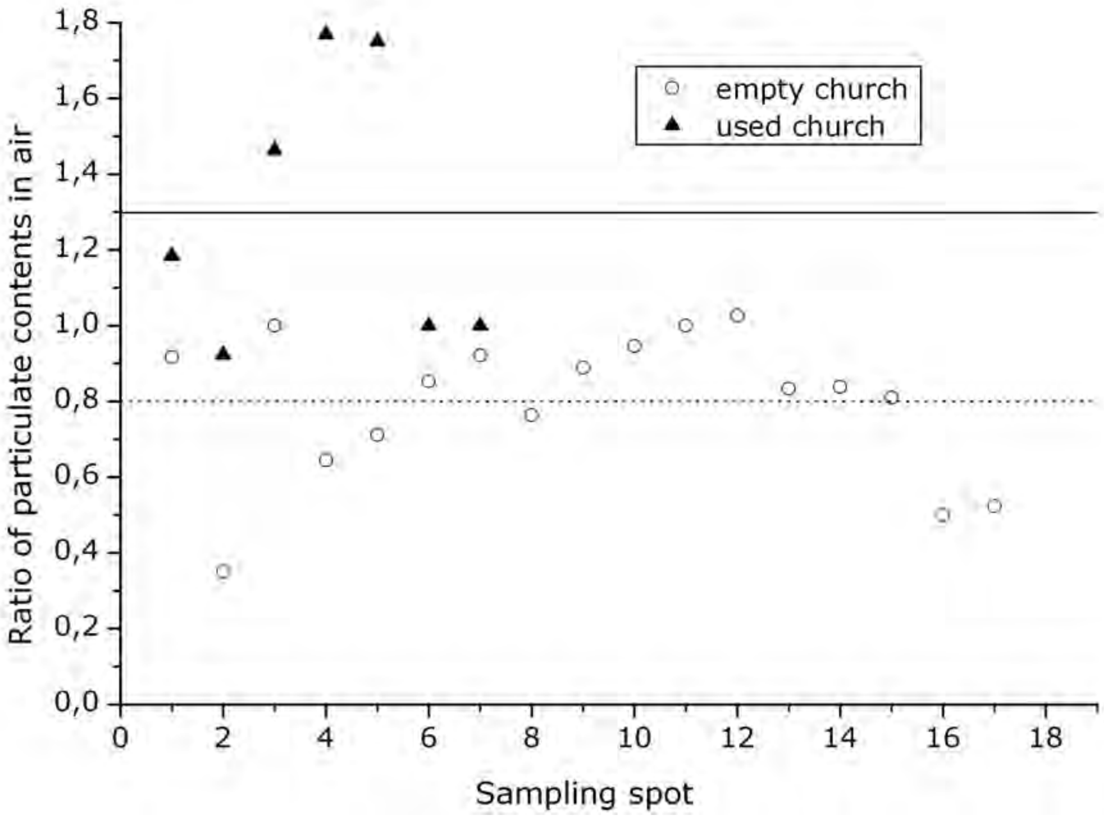

Fig. 12. Ratios of the indoor particulate contents during heating to those in the absence of heating in the adjacent days, determined during three sampling campaigns in both churches.