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Laboratory tests for the evaluation of the heat distribution efficiency of the *Friendly-Heating* heaters

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ABSTRACT

This paper reports the results of three innovative laboratory tests implemented during winter 2013 in the framework of the *Climate for Culture* European Project (2009–2014). Thermal analysis was used to assess the heating efficiency of some heaters with different power consumption, geometric shape and dimensions.

Experimental laboratory results were obtained under natural indoor environmental conditions and the outcomes were applied to a real case study of two churches on the Italian Alps during the Friendly Heating project.

Results provide useful information to help final users and/or conservators to exploit at the best the heating efficiency of some heaters on the basis of the geometric characteristics of the elements and represent helpful advices for their installation, considering both the optimal position for the maximum comfort performance and the need for not exceeding specific risk thresholds for artwork preservation.

1. Introduction

The main purpose of the European Project Friendly-Heating (FH), active 2002–2005, was to study a specific heating method compatible with the conservation of cultural heritage objects, aiming at warming people while leaving church and artworks almost undisturbed in their natural microclimate. This strategy was preferred after comparisons with the other heating systems, by optimizing the pros and reducing the cons. The FH Project selected as case studies two churches in the Dolomite mountains, Italy, with very cold indoor climate, i.e. Rocca Pietore and Santo Stefano di Cadore, to rigorously test the compatibility between preservation needs and thermal comfort for the novel heating system.

The heat sources used in the Friendly Heating project, the thermal comfort on people and the potential impact on pews and on artworks were already studied with laboratory tests, field surveys and model simulations, and the results published in a number of papers [1–5]. In particular, vertical profiles of temperature (T) were monitored using a precision radiometer on a blackbody strip target of the same dimension as a standing person and using a black globe thermometer. This measurement technique required a number of sampling points over a regular grid on the blackbody strip target placed in proximity of the benches. Although each sampling was rapid, e.g. a few seconds, the total monitoring interval lasted a few minutes and some minor fluctuations were possible in the case of turbulence generated by the operator or thermal unbalances in the room.

In order to assess the full 3D heat efficiency distribution of the FH heaters, during the European Project Climate for Culture (CfC), active 2009–2014, laboratory measurements were carried out over a blackbody area using a precision infrared camera. Thermal images of the heat source and of the blackbody area were taken in order to represent all the grid points in the same instant to reduce the sampling time, thus avoiding the disturbance of local air motions and related temperature fluctuations.

This paper presents the results of the laboratory tests performed during winter 2013 and compared with the real case studies.

2. Methodology

2.1. Re-analysis of the case study

The 15th century church of S. Maria Maddalena in Rocca Pietore, situated at 1143 m above mean sea level, is a small massive

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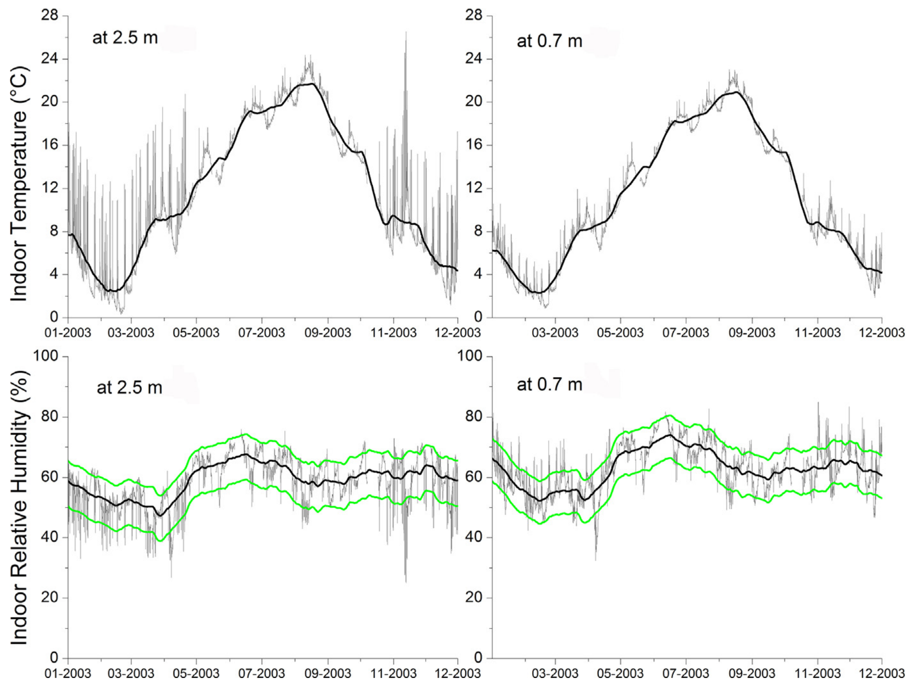

Fig. 1. Top panels: indoor temperature at 2.5 m (left) and 0.7 m (right) above the church floor monitored in the S. Maria Maddalena church at Rocca Pietore for the calendar year 2003. Thick black line 30 days running average (RA). Bottom panels: indoor Relative Humidity at 2.5 m (left) and 0.7 m (right). Thick black line 30 days RA. Thick light green lines 7th and 93rd percentile of the RH fluctuations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

building, 25 m long, with one-meter-stone-thick walls. The nave is 8 m wide and 9 m tall, while the two side chapels are square, with each side measuring 4.5 m. The church contains several artworks: wooden altarpieces, paintings on canvas and panels, choir stalls, a decorated organ-loft with a modern organ, and frescoes. Before the FH Project, the church was provided with warm-air (WA) heating, planned for occasional use, mainly once or twice a week, for around 100 min of operation to mitigate the rigid outdoor winter temperature with minima ranging between −10 and −20 °C. Two grilles, one in the side chapel and the other in the nave (featuring blown-air velocities of 2.7 m/s and 0.4 m/s, respectively), supplied warm air (70–80 °C) inside. After a certain period the WA heating was in operation, some cracks on wood artworks increased in width, disfiguring the faces of the figures of St. Mary Magdalene and St. Catherine in the central part of the altarpiece. The FH monitoring campaign carried out from November 7th 2002 until June 3rd 2004 measured the environmental conditions that caused such dangerous events. Such campaign provided us with the 13-months monitoring data necessary to define the Historic Climate (HC) required for preventive conservation, as stated in the European Standard EN 15757:2010 [6]. Fig. 1 reports the indoor conditions re-analyzed in term of historic climate at two different heights, 0.7 m and 2.5 m respectively. The *T* and relative humidity (RH) values at these levels highlight the air stratification inside the church with stronger temperature peaks and relative humidity drops at higher level when the warm air heating system is in operation. The historic climate reconstruction shows that, during winter, the indoor average temperature is about 6.5 °C at 2.5 m and about 5.5 °C at 0.7 m, while the safe band (i.e. the 7th–93rd percentile of the fluctuations) of indoor relative humidity ranges between 40% and 68% at 2.5 m and 45–70% at 0.7 m. At the higher level (i.e. 2.5 m) RH drops cause shrinkage to wooden objects while at the lower level (i.e. 0.7 m) RH rises cause swelling.

The Church of Santo Stefano di Cadore is also a small massive stone church with three naves, small windows and thick walls. The church was funded in the 13th century, rebuilt in 1684 and a neo classic facade with columned arcade (i.e. pronaos) was added in 1817. It includes a precious organ, paintings and wooden statues. The church inside is some 20 m long, 10 m wide and 8 m tall. The site is at 950 m above the mean sea level, in the middle of a cold valley surrounded by snowed mountains.

Data were re-analyzed using the specific risk assessment tool developed by Martens in 2012 [7] within the CfC Project. The risk for mechanical damage on the wooden base material was assessed for three types of objects preserved inside churches: panel paintings, furniture and statues (Fig. 2).

For panel paintings, the Mecklenburg's plot [8] was used to assess mechanical damage caused by moisture gradients by determining whether yield occurs. The axes in the plot show the starting RH surface response (*y* axis) versus final RH full response (*x* axis). The panel is in safe conditions when its response to the environmental changes remains in the dark grey elastic region; deformation can eventually occur with plastic deformation on the panel (i.e. dots in the light grey area of the plot); finally cracks are likely to occur when the response falls in the failure region (i.e. grey area in the plot).

For furniture a similar approach was used, but over the Bratasz's plot [9] with full response RH (*y*-axis) and annual mean RH (*x*-axis). Elastic behavior is safe (i.e. dark grey area in the plot) while plastic behavior might cause damage (i.e. light grey area).

Finally, for wooden sculpture Jakiela's plot [10] for sloped RH changes was used to assess the risk induced by RH gradients. The level of risk for panel paintings, furniture and statues hypothetically placed at distance (*d*) from the tested heaters has been assessed and reported in Table 1.

The CfC mechanical risk analysis applied to the Rocca Pietore case study reported in Fig. 2 confirms that the central warm air-heating system was not sustainable for conservation as it gave rise to mechanical damages on wooden artworks contravening