Monitoring the Natural Heating of Two Art Nouveau Glass Windows by Infrared Thermography

ABSTRACT

This manuscript presents the results of monitoring the natural thermal variations of two Art Nouveau glass windows from the Casa-Museu Dr. Anastácio Gonçalves in Lisbon, Portugal, by active infrared thermography. The temperature of the glass was found to relate to the environmental temperature and, mainly, to the impinging direct solar radiation. The latter induced an increase in temperature up to 10 °C within one hour, which can produce thermal shock. After sunset, the cooling was also very fast. The increase in temperature also depends on the glass chromophores and the presence of enamel or grisaille. Regarding the effect of external protective glazing, insufficient air ventilation was found to favour the accumulation of warm air in the upper parts of the panels, which could damage the stained-glass windows in the long term.

KEYWORDS

Art Nouveau · Stained-glass windows · Infrared thermography · Vitreous paints · Protective glazing

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INTRODUCTION

Most stained-glass windows comprise parts of building façades, in direct contact with rain and wind, as well as subject to vandalism or air pollutants. For this reason, they are some of the most vulnerable types of glass artworks (Palomar 2013). Rain and pollution are the environmental factors that contribute most to glass alteration (Woisetschläger et al. 2000; Munier et al. 2002; Melcher and Schreiner 2005; Melcher et al. 2008; Gentaz et al. 2011; Lombardo et al. 2014; Palomar et al. 2018b; Palomar et al. 2019); nevertheless, temperature also plays an important role. Environmental temperature and solar radiation increase the temperature of stained-glass windows. This thermal variation can affect the glass and glassy materials of the window. The main harmful signs of degradation due to temperature fluctuations can be observed on enamels and grisailles, resulting in cracking, flaking, and, eventually, the detachment of surface vitreous paint from the glass support due to their different coefficients of thermal expansion. This effect has been observed principally on historic blue enamel (Van der Snickt et al. 2006; Becherini et al. 2008; Attard-Montalto and Shortland 2015) and also on broadly used grisaille paint (Schalm 2000).

This physical incompatibility is directly related to the natural heating of the different materials of a stained-glass window. To assess this heating in situ, it is necessary to use a portable technique, capable of measuring temperature in different areas over time, such as infrared (IR) thermography. Non-destructive and contactless,

Figure 1. *a) Dining room window. Societé Artistique de Peinture sur Verre, 1904 CE, stained-glass window with three lights: H 188 cm × W 64 cm, H 210 cm × W 98 cm, and H 188 cm × W 64 cm; b) Atelier window. Societé Artistique de Peinture sur Verre, 1904 CE, stained-glass window, H 260 cm × W 196 cm.*

this technique can document the thermal behaviours of different targets by quantifying the IR radiation re-emitted by the surface of the objects. An IR camera produces apparent surface temperature images based on calculations from the received IR radiation (emission and reflection) and black body emission laws (Bagavathiappan et al. 2013; Kylili et al. 2014; Palomar et al. 2018a). The photo-thermal signal depends on parameters governing heat diffusion, i.e. thermal conductivity, thermal emissivity, thermal diffusivity, temperature, specific heat, density, and reflection. In addition, these parameters can be correlated with features of the surface, presence of delamination, presence of cracks, internal structure of the material, progress of a physical and chemical transformation, drying, and sedimentation (Bagavathiappan et al. 2013; Kylili et al. 2014).

IR thermography has been used in cultural heritage principally to detect moisture in historic buildings, to assess previous conservation treatments, and to identify hidden structures behind wall paintings (Balaras and Argiriou 2002; Camuffo et al. 2010; Imposa 2010; Morillas et al. 2016). In addition to the application to building structures, IR thermography has also been applied to paintings on canvas or wood (Ambrosini et al. 2010; Sfarra et al. 2011; Gavrilov et al. 2013; Sfarra et al. 2013), tapestries (Dulieu-Barton et al. 2007), books (Riccardi et al. 2010; Doni et al. 2014), and archaeological artefacts (Mercuri et al. 2011; Candoré et al. 2012) to evaluate their condition, to detect hidden damages, and to improve strategies for conservation.

IR thermography studies on historic glass are still scarce (Candoré et al. 2012; Palomar et al. 2018a); nevertheless, IR thermography is a useful tool for the analysis of historic glass windows. Thermography has shown that the different materials in stained-glass windows, including glass, silver stain, enamel, grisaille, lead came, and soldered joints, have different reactions to IR radiation. Glass is heated due to the absorption of mid- and long-wave IR radiation, which leads to a progressive increase of apparent surface temperature. Enamels and grisailles experience a greater increase of their apparent surface temperature as compared with the colourless glass substrate due to absorption in the IR region. This behaviour depends on the thickness and colour of the surface layer (Palomar et al. 2018a).

The main goal of this study was to assess the feasibility of using IR thermography to characterize in situ the potential risk of damage due to thermal impact during the summer solstice of two Art Nouveau glass windows from the *Casa-*

Museu Dr. Anastácio Gonçalves in Lisbon, Portugal. The influences of environmental temperature, solar radiation, and protective glazing on the thermal risk for historic glass windows were evaluated.

MATERIALS AND METHODS

Stained-glass windows

The *Casa-Museu Dr. Anastácio Gonçalves* in Lisbon has two glass windows in Art Nouveau style signed by the *Société Artistique de Peinture sur Verre,* 1904. One is located on the first floor in the Dining room (Figure 1a), and the other is in the Atelier on the second floor (Figure 1b). The latter panel is in a poor state of preservation with loss of the blue and purple enamels and has probably been retouched. Its left and upper panels, as viewed from inside the building, are shadowed by the architectural features. Both windows have exterior protective single-glazing. They are frameless glazing systems that permit the opening of both the glazings and the stained-glass windows. Ventilation slits, measuring less than 5 mm in some areas, separate the different protective glazings and the protective glass from the wall.

Infrared thermography

The characterisation of the surface thermal behaviour of the glass windows was carried out with a FLIR T650sc. The system used for the study comprises a detection device and electronic and computing instrumentation for monitoring. The detection system comprises an IR thermography camera with 20° × 15°/0.3 m field of view, 1.1 mRad spatial resolution, 50 mK at 30 °C thermal sensitivity, 7.5 µm to 13 µm spectral range, and an analysis module. Measurements can be taken from -40 °C to 120 °C, with 1 percent of accuracy of reading. In both windows, a daily monitoring of three images every five minutes was carried out, evaluating environmental temperature and solar radiation as heat sources.

RESULTS

The monitoring of the glass apparent surface temperature showed the influence of the environmental temperature (Figure 2). In the mornings, an increase in the environmental temperature produced progressive heating of the glass. The same relationship was observed during

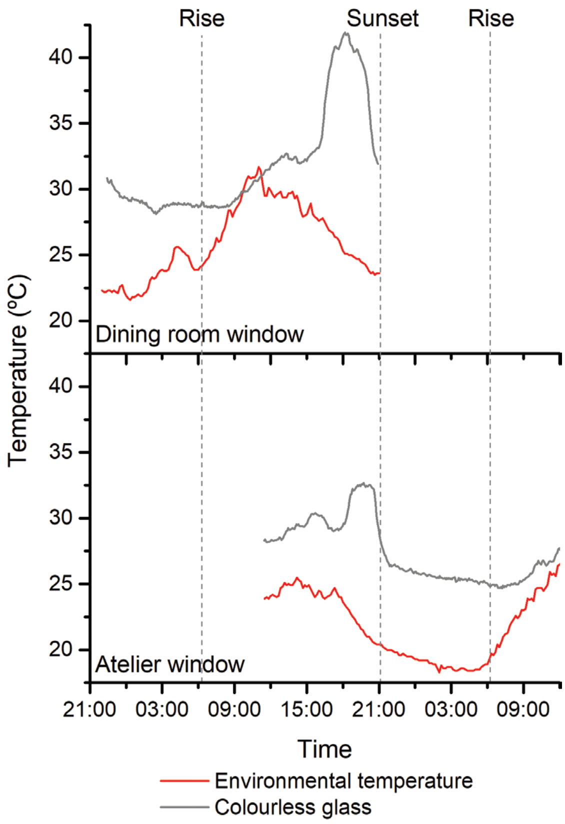

Figure 2. *Thermal variations of the indoor glass surface on a colourless glass from each window, and the environmental temperature in Lisbon measured by the Instituto Português do Mar e da Atmosfera*

the cooling of the glass surface after sunset due to the cooling of the environmental temperature. However, the temperature measured on the interior glass surface was consistently higher than the exterior environmental temperature (Figure 2). This behaviour is due to the greenhouse effect, which heats the different materials within a room, e.g. wood, pottery, textiles, increasing the room's interior temperature and, therefore, the interior glass temperature (Lechner 1990).

On the Dining room panel, the temperature of the colourless glass of the lady's shirt rose to 32 °C as a consequence of the external environmental temperature. In the same way, on the Atelier panel, the temperature detected on the colourless glass in the middle of the panel rose to 30 °C (Figure 2). As expected, during the night, the temperatures decreased on the colourless glass in the Dining room panel to approximately 28 °C and on the Atelier panel to approximately 25 °C.

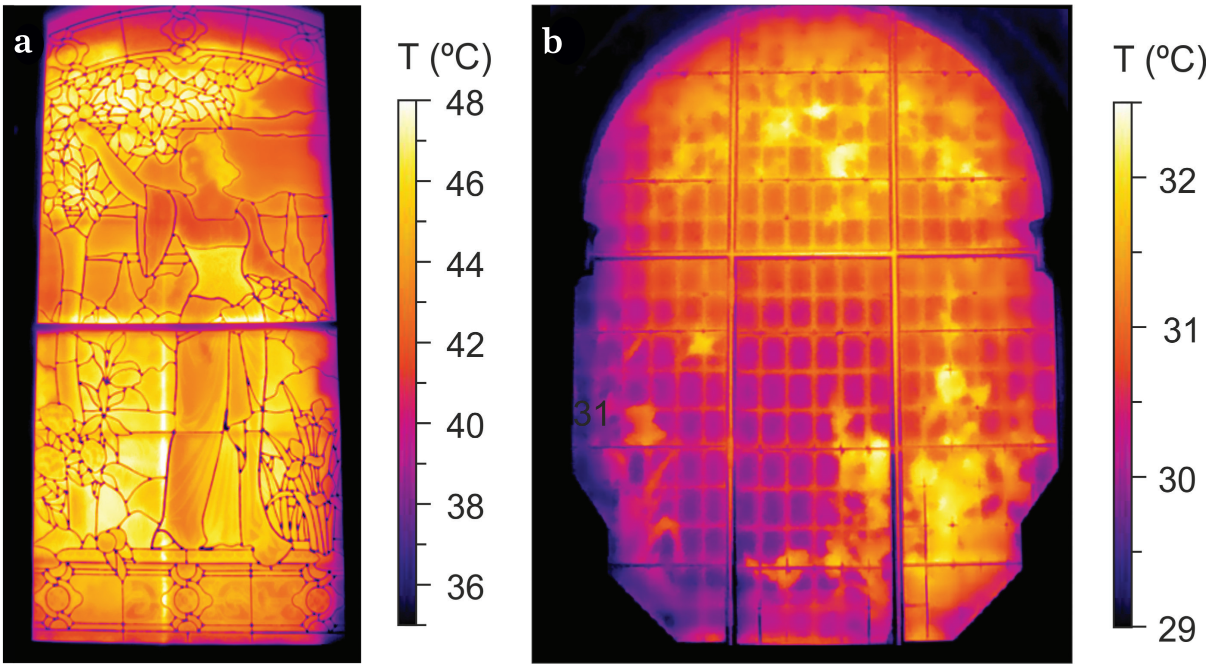

Figure 3. *Apparent surface temperature maps from a) the Dining room stained-glass window at 18:04 and b) the Atelier stained-glass window at 16:23*

Despite the impact of the environmental temperature, the main factor affecting the glass surface temperature is direct solar radiation. In the Dining room panel, the temperature of the colourless glass increased approximately 10 °C during the first hour of direct solar radiation and decreased 9 °C when the sun set behind the buildings (Figure 2). In the Atelier panel, the impact of solar radiation is lessened because of the shorter period of exposure to direct sunlight, the panel orientation, and, possibly, a lower environmental temperature. In the Atelier panel, a total increase of 3 °C during the first 40 minutes of direct solar radiation and a decrease of 5 °C during the hour after sunset were recorded (Figure 2).

A relationship between glass colour and maximum apparent surface temperature was also observed. The colourless glass either does not contain chromophores or the effects of multiple chromophores negate each other; therefore, the colourless glass does not absorb in the near IR region. However, the green glass rendering the vegetation showed the highest apparent surface temperature (Figure 3). The main chromophores of green glass are iron (Fe) and copper (Cu) (Scholze 1980; Fernández Navarro 2003). The Fe^{2+} ions produce two absorptions in the infrared region at 1100 nm and 2100 nm, as well as an absorption band in the visible region at 440 nm (Paul 1990; Möncke et al. 2014). The Cu^{2+} ions produce a broad absorption band at 790 nm due to the electronic transition $^2E \rightarrow {}^2T_2$, with a significant deformation due to the Jahn-Teller effect. The tail of this wide single band enters into the near-IR region (Paul 1990; Fernández Navarro 2003; Möncke et al. 2014).

A high temperature was also detected in the lady's corset, an area with brown colouration. This glass is an amber glass. The chromophore is formed by a mixed tetrahedral coordination, in which one Fe^{3+} ion is surrounded by three oxygen ions bonded to silicon and one sulphide anion bonded to alkali ions for electro-neutrality (FeO_3S). This coordination has two absorption bands at 295 nm and at 425 nm, in the ultraviolet and visible regions, respectively (Weyl 1967; Beerkens and Kahl 2002; Beerkens 2003; Fernández Navarro 2003; Falcone et al. 2011). The probable presence of Fe^{2+} ions and Fe^{3+} ions dissolved in the glass could contribute to the absorption in the IR region.

Enamel and grisaille had a higher apparent surface temperature in comparison with the glass substrate (Figure 3). Variations of up to 2 °C were observed in the same glass piece depending on the absence or presence of vitreous surface layers.

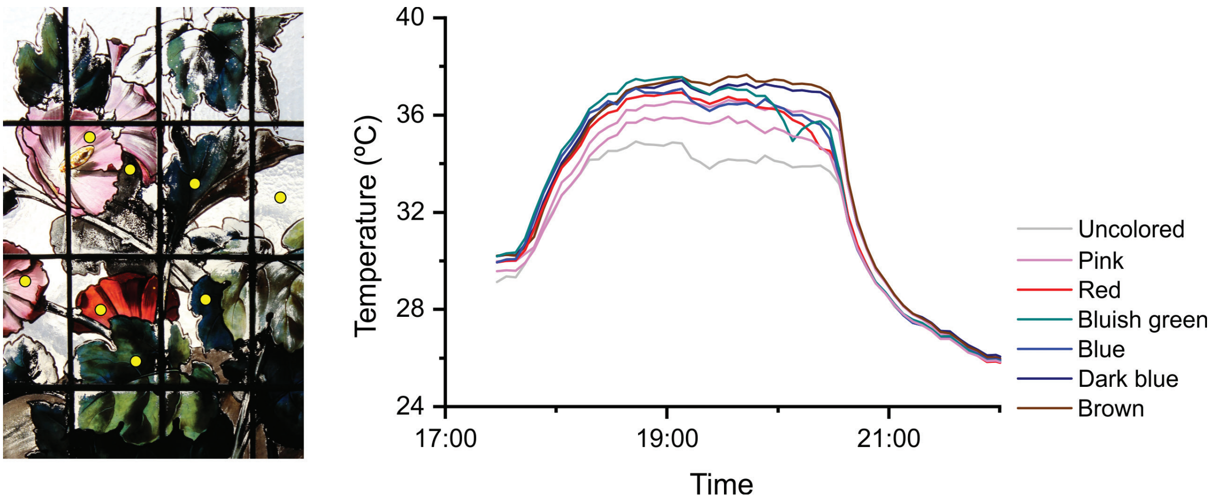

Figure 4. *Detail of the Atelier window, and the thermal variation of different points marked with yellow circles; sample areas average temperature over 2.5 cm²*

High-lead glasses have a lower specific heat than soda-lime silicate glasses (Sharp and Ginther 1951; Fernández Navarro 2003), which means that, for the same incident energy, the temperatures of the enamel and grisaille (with lead glass) will increase more than the glass substrate without surface paint.

The maximum apparent surface temperature also depends on the colour of the enamel and grisaille. The bottom right panel of the Atelier window experienced the greatest temperature range because this area receives the maximum impact of direct solar radiation, due to the orientation and the architectonics of the building. The temperature of this area also increased due to the presence of dark, opaque paint, probably from retouching. The left panel, as viewed from inside the building, is shadowed by the architectural features; however, the iris and the bird, both painted with blue enamel, showed significant increases in temperature in comparison with the surrounding glass: 1 °C during the morning and up to 2.5 °C during direct solar irradiation (Figure 3).

Point analysis on different enamels from the Atelier window confirmed that thermal behaviour depends on the colour of the enamel (Figure 4). The colourless glass had the lowest temperature with direct solar radiation, followed by light-coloured enamels, such as the pale pink. Red, bluish-green, and blue enamels had higher temperatures with direct solar radiation; and, darker enamels, such as brown and dark blue, showed the highest temperatures (Figure 4). These latter materials were dark vitreous paints, some of them from a previous restoration, with iron oxides in their composition, fostering intense absorption of the thermal radiation and, resultantly, increasing the apparent surface temperature (Palomar et al. 2018a). It should be noted that the temperature variation between colourless and dark brown is about three degrees Celsius. This increase in the darker layers favours a higher thermal expansion of the surface layer in comparison with the support glass, which could cause fissures and detachments.

Increased temperature was also detected in the upper part of the Atelier window (Figure 5). Thermal variations of up to 3 °C occurred between the upper and lower parts of the window. This phenomenon relates to the protective glazing, which is placed less than 3 cm from the historic panel with very small slits for ventilation. This nearly airtight protective glazing traps warm air in the upper part of the window panel, increasing the temperature of this part of the panel (Figure 5). If proper ventilation slits were in place, the air would be circulating with a ‘chimney’ effect, allowing warm air be vented at the top, and avoiding its accumulation in the upper part of the panel (Oidtmann 1994; Villaro Amurrio 2016).

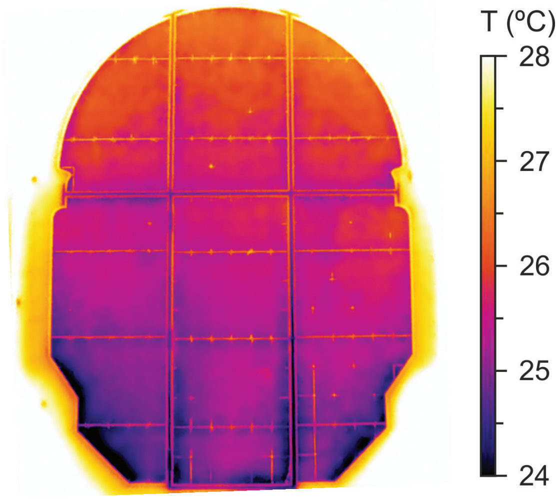

Figure 5. *Apparent surface temperature map of the Atelier window at 01:33*

CONCLUSIONS

The two stained-glass windows from the *Casa-Museu Dr. Anastácio Gonçalves* in Lisbon, Portugal, were successfully investigated with infrared thermography. The main result is that both environmental temperature and solar radiation induce significant thermal fluctuations on stained-glass windows. Solar radiation results in a fast heating of the glass in a short period of time, up to 10 ºC within one hour, which can produce thermal shock on the glass, mainly on the surface layers. After sunset, the cooling is also fast, 5-10 ºC in less than one hour. The green and brown glass absorb the IR radiation, and their apparent surface temperatures increase more as compared to the colourless or clear glass. The same phenomenon was observed on the enamel, where the dark colours presented the highest apparent surface temperatures. Regarding the protective glazing, insufficient air ventilation favours the accumulation of warm air in the upper part of the panel.

ACKNOWLEDGMENTS

The authors thank Dr. T. Marques and Dr. A. Mântua (*Casa-Museu Dr. Anastácio Gonçalves,* Lisbon, Portugal) for the facilities provided to accomplish this research. This work has been funded collectively by the Access to Research Infrastructures activity in the Horizon 2020 Programme of the EU (IPERION CH Grant Agreement n. 654028) and the *Fundação para a Ciência e Tecnologia* of Portugal (Project ref. UID/EAT/00729/2019 and Post-doctoral grant ref. SFRH/BPD/108403/2015).

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