Experimental study on optic and thermal performance of solar control films

David Lopes Lourenço

david.lourenco@ist.utl.pt

Abstract

The concern over economic and environmental issues has led to an increase in building rehabilitation to decrease energy consumption. Part of the high-energy demand is caused by excessive solar gains due to the use of large windows. In order to increase the window's performance, solar control films have been applied to the glazing systems to improve its thermal and solar properties. It is the purpose of this work to study the effect of solar control films. To accomplish that objective, it was carried out an experimental setup in three identical offices; one had no films, other had a film applied in the interior surface of the glazing and the third one had a different film applied in the exterior. During the winter campaign, it was concluded that the offices with solar control film had a better thermal performance than the office without film. In fact, in a cold day, but with high radiation levels, the peak interior temperature was 23.3, 25.5 and 30.2°C, respectively. In the summer campaign, it was concluded that exterior films may be the best solution, since interior films absorb radiation and increase the room temperature trough convection and infrared radiation heat transfer. On the other hand, it was also concluded that the exterior film had the lowest daily illuminance average, which may cause an increase in artificial lighting on cloudy days, which is one of the most drawback of this building rehabilitation solution.

Keywords: Solar control films, energy efficiency, daylight performance, thermal performance, building retrofitting

1 Introduction

Energy dependence and limited fossil resources combined with an increasing concern over climate change has led to efforts in order to decrease energy consumption in the construction sector, in particular in electric consumption of artificial lighting and HVAC systems. In Portugal, due to the scarcity of fossil fuels, there has always been a high-energy dependency. In 2005 oil dependency was 88.8%. Despite the fact that oil dependency has been decreasing – 72.4% in 2012 [1] –, the fact is it still remains very high. For that reason, it is required more actions to improve the energy efficiency of existing building's.

In the European Union, buildings are responsible for 40% of the total energy consumption [2]. Also, the sector is expanding which is bound to increase its energy consumption. Therefore, it is the purpose of EU to reduce energy dependency and greenhouse gases [2]. Through Directive 2010/31/EU on the energy performance of buildings, it is the purpose of the EU that member-states lower the energy consumption by 20% by 2020. In the "Action Plan for Energy Efficiency (2007-12): Realizing the Potential" it is considered that the biggest energy savings comes from the residential and commercial buildings sector, with a savings potential estimated at 27% and 30%, respectively [2].

The energy savings can be achieved, not only in new buildings, but also in existing ones. Whilst new buildings are already designed for new and more demanding regulation, existing ones have often inadequate energy and thermal performance, increasing its energy consumption.

Windows are one of the elements that affects the energy performance and luminous quality in both residential and commercial buildings. For that reason, in recent years, window technology has seen an increase in terms of energy efficiency and developing high performance solutions. However, to let daylight into the interior with the potential of electric savings in artificial lighting and to increase the work environment, buildings have very high window-to-wall ratios. This has led to an increase in solar gains that may affect energy consumption in order to maintain thermal comfort levels. These solar gains are more severe in countries like Portugal that have long cooling seasons (Mediterranean climate).

One way to modify the solar-optic properties of glazed systems is to apply solar control films to their interior or exterior surface. These films have spectral characteristics that will change both solar and optical properties of glazing systems. Recent studies have shown the energy potential savings associated with these films.

In Shanghai, Yin, R *et al.* [3] studied the effect of applying solar window films in a commercial building with large glazed areas. Through simulation, they concluded that the position of the installed window film and the configuration of the original film significantly influence the effect of window film. They also concluded that the film can decrease the solar heat gain coefficient by 44% and 22% if applied on the exterior and interior of the existing windows, respectively and that applying an exterior film to the case study would lead to an 8% in overall electric savings.

Xamán, J. *et al.* [4] presented a numerical study in a double pane window with solar control film for warm and cold climates. They concluded that, for warm climate the use of solar control film is highly recommended since it can reduce the amount of energy gained within 52% compared to a double pane without solar control film. For cold climate, the amount of energy gain through the system is reduced by 10% when compared the double pane window. Noh-Pat, F *et al* [5] made a similar study and concluded that the reduction in energy gain of a double glazing unit with a solar control film on its surface was 55% compared to the double glazing unit without solar film, similar to the study by Xamán, J. *et al*.

Li, C. *et al.* [6] developed simulation models to evaluate the energy savings potentials of solar window films applied onto glazing of three different function rooms in Hong Kong: office, shopping mall and hotel guest room. The best results were found in office applications with savings in the range of 77 to 90 kWh/year per unit area of solar film. For the other rooms the savings range from 44 to 57 kWh/year.

To avoid the problem of glare, excessive brightness and thermal discomfort, occupants tend to block the windows with internal shading devices, resulting in poor daylighting performance. In Hong Kong, Li, D. *et al.* [7] made field measurements on solar control film coatings to analyze the reduction of energy consumption on offices with large glazed areas. They concluded that the solar heat reduction was around 30% and 50% for pure diffuse and direct solar radiation, respectively. They also found that the visible transmittance of the film was 76%. The case study indicated that electric savings due to solar control films could be in order of 55 Wh per square meter of floor area per day.

Moretti, E. and Belloni, E. [8] carried a full-scale experimental setup and numerical analysis on two similar offices, with and without solar control films in Italy. They observed that the solar control film reduced the incoming solar radiation, around 60%. During sunny days, window films allowed a reduction of about 2-3°C of the indoor air temperature. They also simulated the energy consumption of the two offices, that showed a decrease of about 29% in the cooling energy demand in the office with film. However, the heating energy demand increased about 15% in the same office.

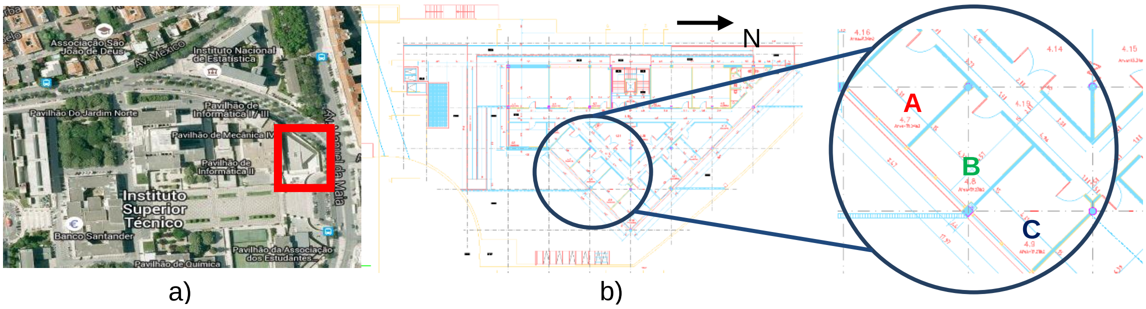
Solar control films have the potential to improve the energy performance of glazing systems, due to the reduction of the SHGC (Solar Heat Gain Coefficient) and the solar transmittance (τ_{sol}) but, they also reduce visible transmittance (τ_{vis}), which in cloudy days may increase electric consumption due to artificial lighting.

It is the purpose of the present study to evaluate experimentally both the thermal and luminous performance of glazing systems with and without solar control films. In order to accomplish that, it was carried an experimental setup in three similar offices. In the first office, it was applied a solar control film to the exterior surface of the glazing system, the second was left with the previously applied film on the interior surface and the third, which was considered as reference, without film. The experimental setup consisted in measuring air and surfaces temperatures as well as illuminance levels to evaluate the thermal and luminous performance of solar control films.

2 Case Study

The experimental setup was carried out in the *Mecânica III* building located in *Instituto Superior Técnico* in Lisbon Figure 1a. This building was built in the year 2000 and has two upper floors. The second floor consists mainly of individual offices. It was made a previous attempt to reduce thermal and optical discomfort by applying a solar control film (R35 SR HPR) to the interior surface of the glazing system. Three adjacent offices were selected: A, B and C (Figure 1b). All offices have the same area (19m^2), height (2.95m), solar orientation (south-east SE) and occupation (individual with sporadic meetings). The glazing system of the reference case (office C) is a conventional double glazing filled with air (6+12+4mm). In office A was applied a solar film (RHE20 SI ER HPR) on the exterior surface of the glazed system (Figure 2a); office B was left with the interior film previously applied (R35 SR HPR) (Figure 2b); in the office C the previously installed window film was removed (Figure 2c).

The thermal and solar-optic properties of the three glazing systems were calculated using Optics and Window software (Table 1) and consist of: Shading Coefficient (SC), Solar Heat Gain Coefficient (SHGC), visible transmittance (τ_{vis}), visible reflectance of the exterior surface ($\rho_{f,vis}$), visible reflectance of the interior surface ($\rho_{b,vis}$), solar transmittance (τ_{sol}) solar reflectance of the exterior surface ($\rho_{f,sol}$), solar reflectance of the interior surface ($\rho_{b,sol}$), absorptance of the exterior pane (α_1), absorptance of the interior pane (α_2). The thermal transmittance (U) was the same for the three offices, 2.82 W/m^2°K. There is an important shading effect on the exterior façade of all offices thanks to the configuration of the building that can be seen in Figure 1b. This effect will provide shade around 12h and will have an important outcome on the obtained records, as will be shown later.



a) b)

Figure 1 - Location of the case study: a) Instituto Superior Técnico; b) Mecânica III building

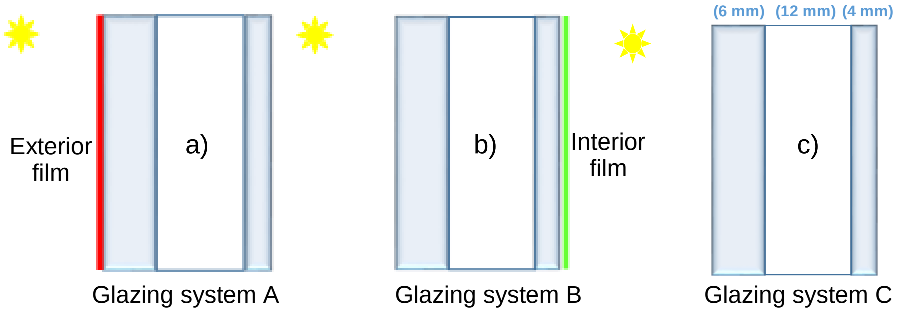


Figure 2 - Glazing system A (a), glazing system B (b) and glazing system C (c)

Table 1 - Thermal and optic properties of the three glazing systems

Thermal and optic properties	SC	SHGC	τ_{vis}	$\rho_{f,vis}$	$\rho_{b,vis}$	τ_{sol}	$\rho_{f,sol}$	$\rho_{b,sol}$	α_1	α_2
Office A (film RHE20 SI ER)	0.21	0.18	0.15	0.70	0.56	0.10	0.62	0.41	0.27	0.01
Office B (film R35 SR HPR)	0.46	0.40	0.26	0.45	0.46	0.17	0.34	0.50	0.19	0.31
Office C (no film)	0.86	0.74	0.80	0.14	0.15	0.66	0.12	0.12	0.15	0.07

3 Experimental setup

Field measurements were carried out simultaneously in the three office rooms. In order to evaluate the thermal and visual performance of the glazing systems with and without solar control film. It was measured: *i)* both air and surface temperatures on the interior and exterior of each office; *ii)* heat flux between the interior surface of the window and the interior of the offices; *iii)* vertical interior and exterior solar radiation in the offices; *iv)* vertical and horizontal exterior solar radiation on the rooftop; *v)* interior vertical illuminance; *vi)* exterior horizontal illuminance on the rooftop.

In each office, it was used 9 thermocouples type T for measuring air and surface temperatures both exterior and interior (Figure 3). It was also used a heat flux sensor for the heat flux. Both the vertical interior and exterior solar radiation were measured using a LI-COR LI200 pyranometer. In addition, the interior vertical illuminance in all offices was measured by a LI-COR 210R luximeter. In the rooftop, it was used a BF5 pyranometer to measure both global and diffuse horizontal radiation and a Kipp&Zonen pyranometer for the exterior vertical radiation. Figure 4 shows a schematic with the positions of each sensor.

a) b) c)

Figure 3 - Surface thermocouples (a), interior thermocouple and schematics of the thermocouples used in the glazing system (c)

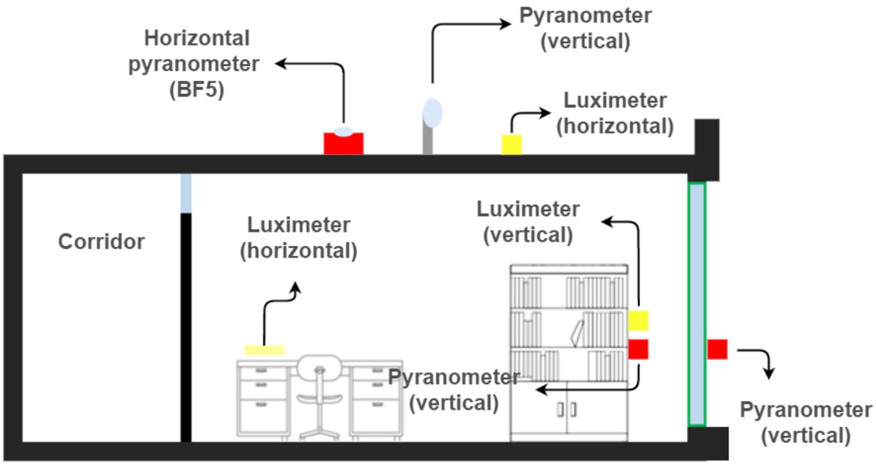


Figure 4 - Schematics with all the pyranometers and luximeters used both in each office and on the rooftop

4 Results and discussion

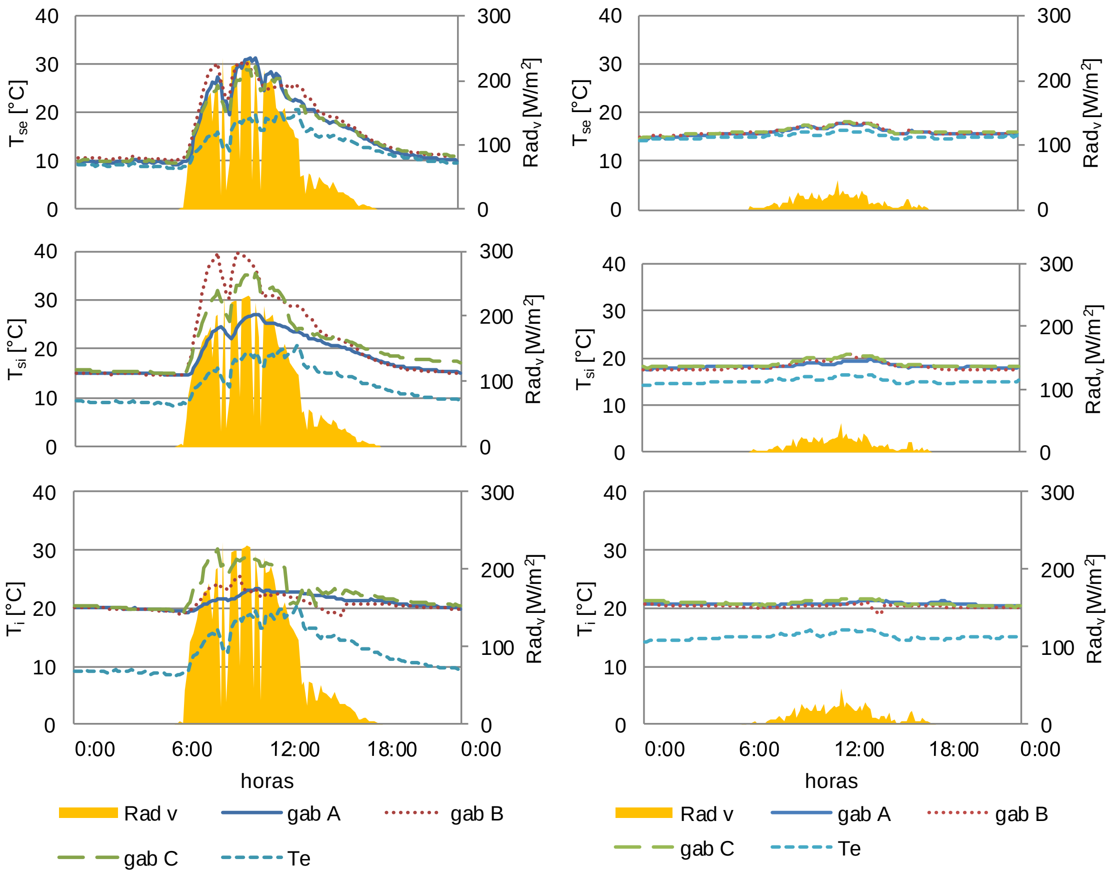
The experimental setup was carried in two distinct periods on 2016: the first was during the winter period; and the second was during the summer period. In this chapter, the results for typical days both in the winter and summer campaign are presented. For the present study the following parameters were recorded: *i)* outdoor (T_e) and indoor (T_i) air temperatures; *ii)* exterior (T_{se}) and interior (T_{si}) surface temperatures; *iii)* vertical global radiation measured both on the offices exterior ($Rad_{V,office}$) and on the rooftop ($Rad_{V,roof}$); *iv)* exterior horizontal illuminance measured on the rooftop ($E_{ext,H}$); *v)* vertical illuminance measured on the offices interior ($E_{int,V}$).

4.1 Winter campaign

The winter campaign started on 11 March and lasted until 16 April. For the typical days in winter it was considered the lowest daily average outdoor air temperature (T_e) day – DMF – and the lowest daily average (on the insolation period) vertical radiation day – DmR – measured on the offices exterior ($Rad_{V,office}$). Table 2 shows the daily average of the outdoor air temperature (T_e) and the daily vertical radiation ($Rad_{V,office}$) for both days.

4.1.1 Temperature

Figure 5 shows the outdoor (T_e) and indoor (T_i) air temperatures, the exterior (T_{se}) and interior (T_{si}) surface temperatures and the exterior vertical radiation ($Rad_{V,office}$) on both winter days, DMF and DmR. Both glazing systems with film have similar T_{se} values. In fact, for DMF glazing B has slightly higher daily average (16.9°C), whereas office A has a daily average T_{se} of 16.1°C. This can be explained by the fact that the value of the solar reflection (Table 2) of glazing system A (exterior film) is higher than that of glazing system B (interior film) which leads to a reduction of the incoming solar radiation through glazing A. In addition, the interior film of glazing B reflects part of the solar radiation towards the exterior glass, which, in turn, will increase its temperature. The values of T_{si} are higher in glazing B, which is in accordance with the properties calculated before (Table 2), namely the glazing absorptance. This property is significantly higher in glazing B and will lead to an increase of the solar radiation absorbed by the interior glass which, in turn will cause a rise of T_{si}.



a) b)

Figure 5 – Outdoor (T_e) and indoor (T_i) air temperatures, exterior (T_{se}) and interior (T_{si}) surface temperatures and global vertical radiation ($Rad_{V,office}$) for the days DMF (a) and DmR (b)

Figure 5a also shows that, regarding T_i, for DMF, the thermal performance of both films was very similar. In fact, the major difference was for office C (without film). In terms of maximum temperature value, they were respectively 23.3°C, 25.5°C and 30.2°C for offices A, B and C, which shows the effect of both films in reducing indoor temperature. This effect is due to the reduction of both solar heat gain coefficient (SHGC) and solar transmission (τ_{sol}) caused by applying these films on the glazing surface. It may seem that applying the film on the exterior surface slightly increase the thermal performance of the glazing system, but film A has also the lower values of those solar properties (Table 2).

For the DmR (Figure 5b) the temperatures recorded for all offices were very similar because the outdoor air temperature was practically constant throughout the day thanks to the low levels of solar radiation.

4.1.2 Solar Radiation

Figure 6 shows the difference between the vertical solar radiation measured on the offices exterior ($Rad_{V,office}$) and on the rooftop ($Rad_{V,roof}$). Since the exterior vertical illuminance ($E_{ext,V\ calc}$) was calculated based on the exterior horizontal illuminance ($E_{ext,H}$) measured on the rooftop, this difference (in the vertical radiations) will have an important effect because it proves that the calculated vertical illuminance ($E_{ext,V\ calc}$) will be different than the actual exterior illuminance on the offices façade.

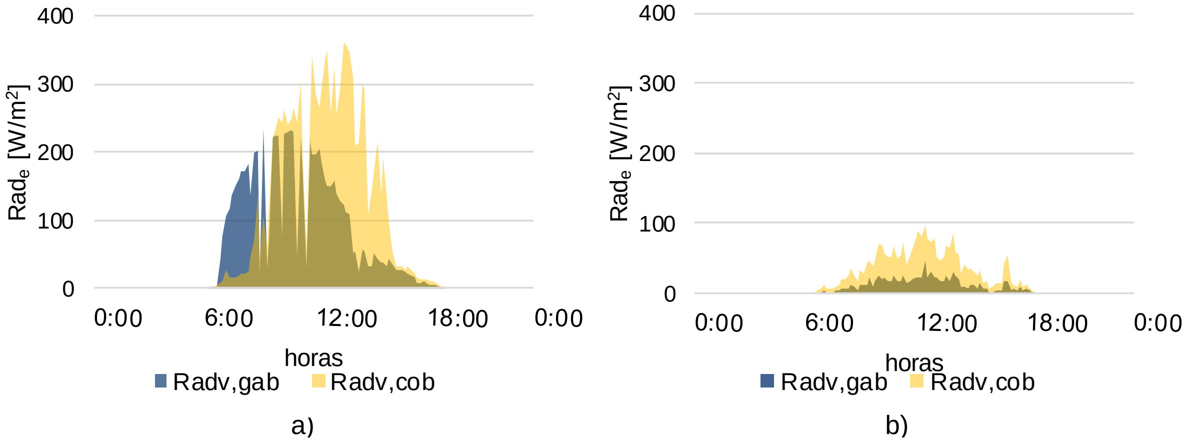


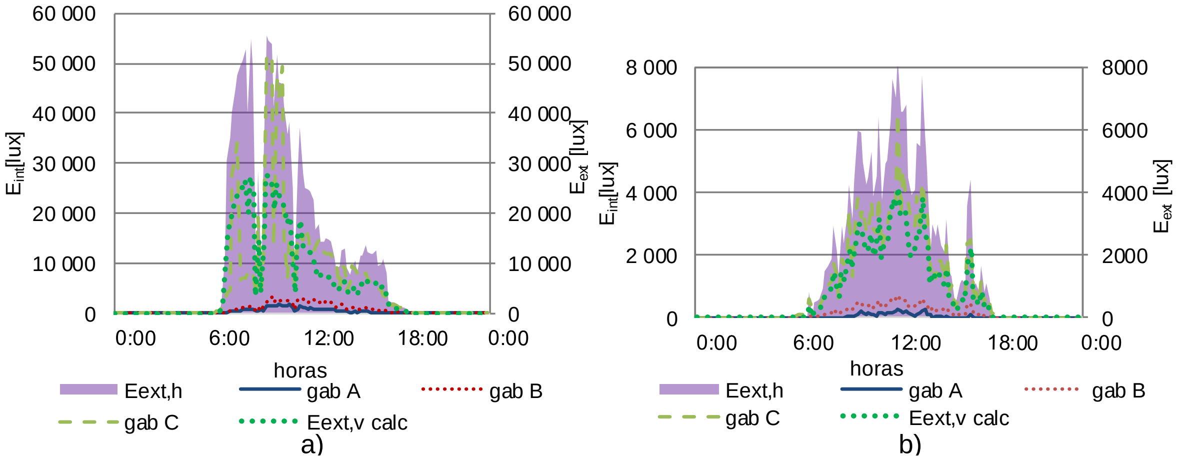
Figure 6 – Vertical radiation measured on the offices exterior ($Rad_{V,office}$) and on the rooftop ($Rad_{V,roof}$) for the days DMF (a) and DmR (b)

4.1.3 Illuminance

Figure 7 shows the values of the exterior horizontal illuminance measured on the rooftop ($E_{ext,H}$), the vertical illuminance measured on the offices interior ($E_{int,V}$) and the calculated value of the exterior vertical illuminance ($E_{ext,V\ calc}$) based on the exterior horizontal illuminance ($E_{ext,H}$), for the days DMF and DmR. Due to significant differences between the two days the vertical axis of both graphics has different scales. It can be seen on Figure 7 a significant difference between the interior illuminance levels of the offices with applied film (A and B) and the interior illuminance of office without film (C). To confirm this difference, field tests were carried in real time that presented similar results.

The daily average (on the insolation period) of the interior illuminance, respectively for offices A, B and C was 301 lx, 675 lx and 6239 lx for DMF and 127 lx, 274 lx and 1812 lx for DmR. When comparing the interior illuminances ($E_{int,V}$) with the calculated exterior illuminance ($E_{ext,V\ calc}$), it can be concluded that the values of $E_{int,V}$ were lower than previously anticipated, according to the previously calculated properties (Table 1), in particular visible transmittance; 0.15 for glazing A, 0.26 for glazing B and 0.80 for glazing C. This difference can be explained by observing Figure 6, where there was a significant difference between the values of vertical radiation on the offices exterior and on the rooftop. Taking this into account, it can be concluded that the exterior vertical illuminance calculated ($E_{ext,V\ calc}$) is higher than the effective exterior illuminance on the office exterior, hence the lower level of interior illuminance recorded.

It can also be concluded that office C (without film) has excessive illuminance levels that may cause visual discomfort, which was one of the reasons for the previous application of film on the interior surface of the glazing system. Also, the fact that the offices with film, particularly office A (lower visible transmittance), present very low levels of illuminance may cause an increase in electric consumption due to the use of artificial lighting. However, this seems not to be the case since, for offices A and B, weren't register any sudden peaks in interior illuminance (indicating turning on the artificial lighting) and, on occasional visits to collect data, it was not noticed the use artificial lighting. The reason why, is because people have more tolerance to low levels of illuminance if it is natural lighting, as explained by dos Santos [9].



a) b)

Figure 7 – Interior vertical illuminances ($E_{int,V}$), exterior horizontal illuminance ($E_{ext,H}$) and calculated exterior vertical illuminance ($E_{ext,V\ calc}$) for DMF (a) and DmR (b) (the vertical axis have different scales)

Table 2 – Daily average of the outdoor air temperature (T_e) and vertical radiation ($Rad_{V,office}$) of the typical days

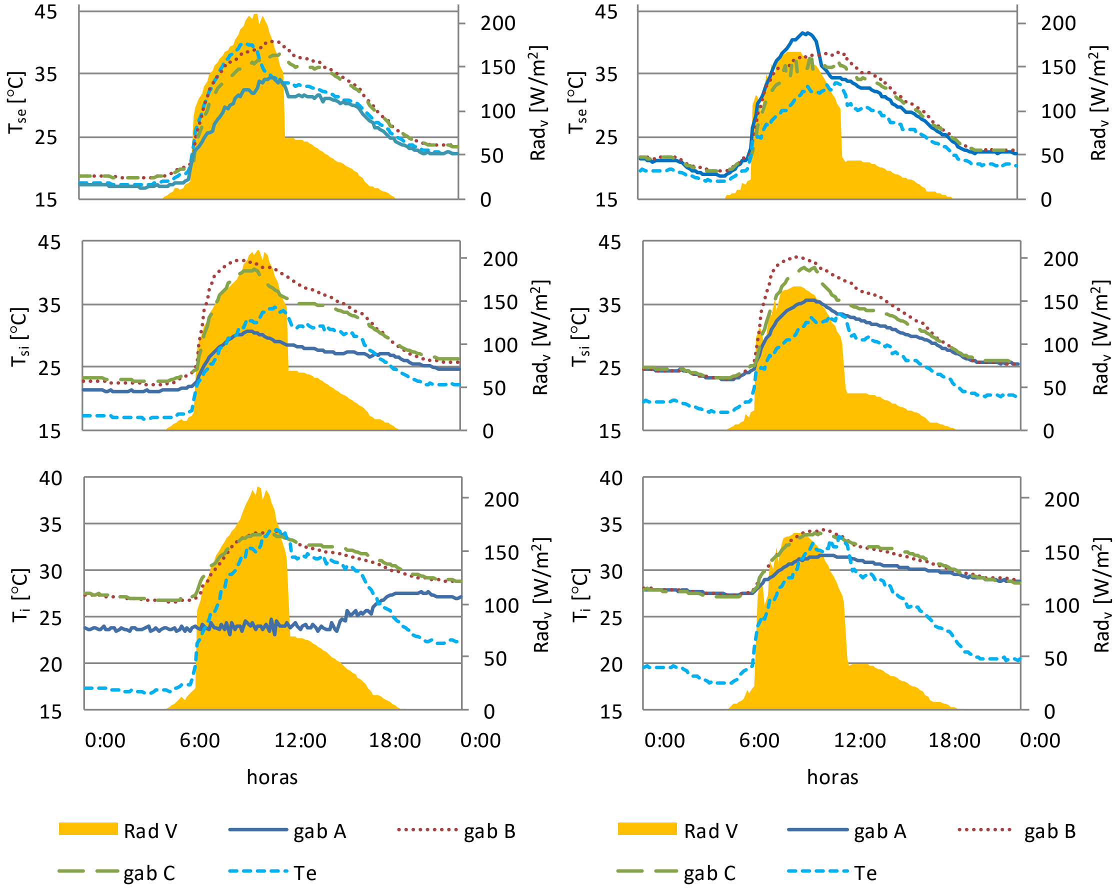
	Winter			Summer	
	T_e [ºC]	$Rad_{V,office}$ [W/m^2]		T_e [ºC]	$Rad_{V,office}$ [W/m^2]
DMF (31/03)	12.7	93.0	DMQ (08/06)	27.4	67.5
DmR (14/04)	15.1	11.4	DMR (26/06)	24.9	82.5
			DSC (12/06)	24.2	62.3

4.2 Summer campaign

The summer campaign started on 28 May and lasted until 28 June. Initially it was only considered two days, The day with the highest daily average outdoor air temperature (T_e) – DMQ – and the day with highest daily average (on the insolation period) vertical radiation – DMR – measured on the offices exterior ($Rad_{V,office}$). After the analysis of both DMQ and DMR days it was found that, thanks to high outdoor temperatures (T_e) all occupants used air-conditioning systems, therefore influencing both air (T_i) and surface (T_{si}) interior temperatures. Because of this influence it was also analyzed the next day with the highest daily average T_e, but without the influence of the air-conditioning system – DSC. Table 2 shows the daily average of the outdoor air temperature (T_e) and exterior vertical radiation ($Rad_{V,office}$) for all three days.

4.2.1 Temperature

Figure 8 shows the outdoor (T_e) and indoor (T_i) air temperatures, the exterior (T_{se}) and interior (T_{si}) surface temperatures and the exterior vertical radiation ($Rad_{V,office}$) on day DMR (highest levels of radiation) and DSC (summer day without the influence of the air-conditioning system).



a) b)

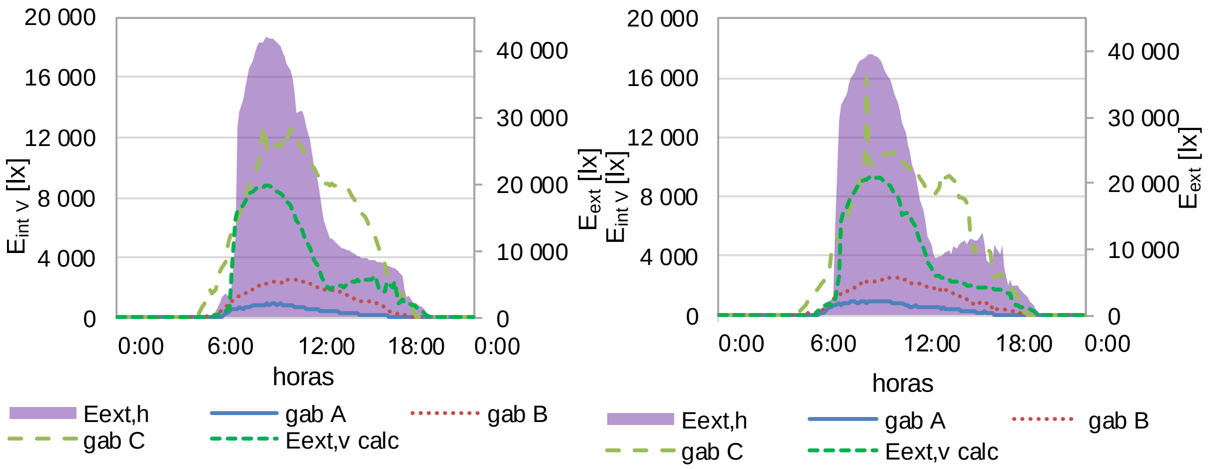
Figure 8 - Outdoor (T_e) and indoor (T_i) air temperature, exterior (T_{se}) and interior (T_{si}) surface temperatures and global vertical radiation ($Rad_{V,office}$) for the days DMR and DSC

For the day DMR (Figure 8a) it can be observed that the air-conditioning system of office A was turned on, since the indoor air temperature (T_i) was practically constant throughout the day and only saw an increase around 18h, contrary to the tendency of both the outdoor air temperature (T_e) and the solar radiation ($Rad_{V,office}$). This will most likely influence both exterior (T_{se}) and interior (T_{si}) surface temperatures. Regarding the other offices, since room temperature (T_i) was above 30°C, it can be concluded that the air-conditioning was of, therefore neither temperatures were affected. Figure 8a also shows that, in terms of indoor temperature (T_i), both offices had virtually the same values. This shows that interior film may not be the best solution thanks to the film's higher absorption of solar radiation that causes an increase in T_{si} (as shown on Figure 8), which in turn, may increase T_i trough convection and radiation.

For the day DSC (Figure 8b) it can be evaluated the thermal performance of the three glazing systems. Once more, offices B and C present similar values of T_i. However, for office A it can be observed the indoor temperature is slightly lower than the other offices. The daily average room temperature was respectively 29.4°C, 30.3°C and 30.2°C for offices A, B and C. For the summer campaign, it was observed a slight decrease in thermal performance of both glazing systems A and B compared to the winter campaign. This occurred due to the significantly increase of the outdoor air temperature in comparison to the winter period. In fact, both outdoor temperature and exterior solar radiation play an important part in the thermal performance of glazed systems. Both films lower the solar-optic properties of glazing systems A and B, while maintaining the thermal transmittance (U) equal to the glazing system C (chapter 2).

4.2.2 Illuminance

Figure 9 shows the values of the exterior horizontal illuminance measured on the rooftop ($E_{ext,H}$) and the vertical illuminance measured on the offices interior ($E_{int,V}$). It also shows the calculated value of the exterior vertical illuminance ($E_{ext,V\ calc}$) based on the exterior horizontal illuminance ($E_{ext,H}$), for the days DMQ (highest daily average outdoor temperature) and DMR (highest daily average radiation).



a) b)

Figure 9 - Vertical illuminance on the offices interior ($E_{int,V}$), horizontal iluminance measured on the rooftop ($E_{ext,H}$) and calculated exterior vertical illuminance ($E_{ext,V\ calc}$) for DMQ (a) and DMR (b)

The interior illuminance levels on the vertical plane were in crescent order respectively 525 lx, 1324 lx and 6212 lx for offices A, B and C for the day DMQ and 514 lx, 1351 lx and 6575 lx for the DMR in the same order.

Once more it can be concluded that office C has problems in terms of visual comfort, particularly around 10h on both days. Offices A and B had lower values than what was anticipated, based on the properties calculate beforehand (Table 1), namely the visible transmittance. As seen for the vertical radiation (Figure 6), there is a considerable difference between the values recorded both on the offices exterior and the rooftop. This means that, the calculated exterior vertical illuminance ($E_{ext,V\ calc}$), based on the horizontal illuminance measured on the rooftop ($E_{ext,H}$), will have higher values than the effective exterior radiation on the offices exterior.

5 Conclusions

In order to evaluate the thermal and optical performance of solar control films, a field experimental campaign was carried on three similar office rooms: one had film apllied to the exterior (office A) surface of the glazing system, other had another film applied to the interior surface (office B) and the last office had no film (office C). Measurements were performed during both winter and summer campaigns, in order to analyze typical days for each campaign. At the same time the solar-optic properties of each glazing system were numerically determined using Optic and Window software, in order to infer the thermal and optic performance of each glazing system.

During winter campaign, it was concluded that the glazing system A had the better thermal performance. However, this can't only be atributed to the position of the film (on the exterior surface) itself, since glazing system A had lower values of SHGC and solar transmission, as well as higher solar reflectance than glazing system B.

For the summer campaign it was concluded that both glazing systems with film had a worst thermal performance in comparison with the winter period. This was due to the fact that solar films don't reduce the value of the thermal transmittance (U) of the glazed systems and, with higher outdoor air temperatures characteristic of summer time, the thermal performance of both glazing systems (A and B) was lower in comparison to the winter campaign. In fact, glazing system B had a similar performance to the glazing system without any film (glazing system C) because the film applied to the interior surface absorbs more solar radiation, which led to a higher interior surface temperature of the glazing system B which, in turn, through convection and radiation, caused an increase on the indoor room temperature.

Regarding illuminance levels, it was concluded that the interior vertical illuminance for the three offices had lower values than what was anticipated, based on the previously calculated optic properties of each glazing system. Solar control films greatly reduced incoming visible light, especially in cloudy days which may lead to an increase in electric lighting. However, in this study that was not the case. In fact, it was observed that the occupants had a high tolerance towards low levels of indoor natural illuminance, which is in accordance with previous studies made in this field [9].

In conclusion, solar control films have the potential to improve the thermal performance of glazing systems and, consequently, decrease the energy consumption in HVAC systems. However, due to lower indoor illuminance levels, which in cloudy days may increase the use of electric lighting, their application should be carefully considered in locations with predominantly overcast sky conditions, since the increase in electric lighting may be higher than the reduction in HVAC systems savings.

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