Experimental evaluation of comfort and visual conditions on the interior of buildings through the application of films on the glazed

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Abstract

In order to improve thermal comfort and visual comfort in the indoor environment of offices in IST-Taguspark campus, a PDLC type intelligent film, and a reflexive film with solar protection were implemented in two offices room in 37,76% of the glazed area.

Thermal comfort was analyzed using indoor temperatures and relative humidity monitoring, as well as external temperature and irradiance for two conditions: the first one for opaque PDLC and reflexive film, and in the second for the transparent PDLC. The variables were compared with those obtained in a reference office room without films.

To analyze its impact on visual comfort, two zones were created, one next to the window (ZJ) and another in the work zone (ZT), where the illuminance values were obtained in the reference office room, in the office with PDLC opaque and transparent and in the office with reflexive film in the presence of essentially direct and diffuse radiation for specific time.

It was found that, comparatively to the reference office, PDLC and reflexive film are able to slightly reduce the internal temperature (ΔT>-1ºC), as well as the cooling needs.

Due to its radiation control, PDLC induces an improvement in the visual comfort when in the presence of essentially direct radiation. Further, although in the presence of essentially diffuse radiation the reference presents an average illuminance value slightly above 500 lx, the PDLC allows values to obtain similar values, while reflexive film does not show such significant improvements in the illuminance obtained values.

Keywords: Solar gains on building windows; PDLC switchable smart film; Reflexive film with solar protection; Thermal comfort; Visual comfort.

1. Introduction

Building sectors are responsible for 30%-40% of the overall primary energy use [1] and according to the International Energy Agency, heating and cooling needs in buildings correspond to one third of the building consumption [2], in order to ensure inside temperatures that promote thermal comfort.

Windows are the principal component that contributes to heat and loss gains [3] and particularly, cooling needs due to solar radiation. To improve this construction component and reduce its effects on the energy consumption and increase energetic sustainability, technology evolves.

In this way, there are technologies that allow the solar control in the glazing like photovoltaics, coatings or materials, that offer performance in terms of building saving [4]. Due to constant transparency, visual comfort can be impaired. Switchable glazing or smart windows have dynamic optical properties that can be changed electrically or due to environmental conditions, namely solar factor and radiation transmittance [5]. This technology can reduce 30% of energy consumption [6], control the incident radiation and glare according to occupant comfort [7].

Smart windows can be considered passive if its properties are changed by environmental conditions or be considered active if changed electrically. There are two types of passive windows that contrary to active windows, possess a modulation that cannot be directly changed, namely thermochromic where optical properties can be changed by temperature influence. Usually its transparency is achieved with low temperatures and when exposed at high temperatures this material gets dark [8] or photochromic that change its coloration when exposed to light.

There are four types of active windows such as electrochromic, polymer dispersed liquid crystals (PDLC), gasochromic and suspended particles. Electrochromic material has been well developed for building windows [6] and promising to reduce heating and cooling costs and electricity in buildings [5] . Tungsten trioxide (WO_3) is the most common electrochromic material due to higher stability, and this glazing does not require continuous power supply to keep it on operation mode [4].

Particle suspended devices are compounded by a spherical particle suspended in organic fluid between two transparent conductors, usually ITO [9]. When there is no electric current, particles absorb light and decreasing the amount of light transmitted[10].

Polymer dispersed liquid crystals (PDLC) are implemented in this case study and can be placed on existing windows. In its composition, liquid crystals are dispersed in a polymer, usually nematic ones. In an off operation state (PDLC opaque), the particles are disoriented and when the light reaches its surface is scattering. In the application of electric power, liquid crystals are oriented and become transparent allowing radiation passage.

Beyond the smart films, there are adhesive ones that despite its simplicity, when compared to smart films, allow the reduction of the cooling and heating needs [11]. This type of film can be applied on the interior or exterior glass giving it UV and IR radiation protection, enhancing the natural light by entering and increasing the thermal performance.

The purpose of this work is to analyze the experimental results and understand the impacts of PDLC and reflexive film with solar protection on thermal and visual comfort in 3 office rooms. Thus, SmartCling™ Selft Adhesive Smart tint (PDLC) and adhesive film D' Deco UV Ref.Safe- Linea Hogar were used and implemented in two office rooms, in 50% of the existing glasses with an area of 1,75 m^2, corresponding to 37,76% of the glazed area. To understand their impact, these office rooms were monitored, and the values were compared to a reference room (with no film applied). Two situations were generated to analyze the thermal comfort, the first one with PDLC in opaque and the second one in transparent mode. To analyze the visual comfort, two situations were also performed. One with direct radiation (clean sky) and another with diffused radiation (sky with clouds) and created the ZJ and ZT with the purpose to analyze illuminance in the office room near the windows and in the occupant work zone.

2. Case Study

2.1 Building Characterization

In this case study office rooms are in Instituto Superior Técnico, placed in Taguspark- Oeiras. The three office rooms are the same area and the glass façade are oriented to south-west (figure 1).

The global heat transfer coefficient (U) of the building, assumes low values for its construction, especially for its roof and external walls. The roof can be separated in three parts, depending on its concrete thickness an its U values are 0,49 $W.m^{-2}.k^{-1}$,0,5 $W.m^{-2}.k^{-1}$ and 0,519 $W.m^{-2}.k^{-1}$ and external wall above the glazed has an U=0,567 $W.m^{-2}.k^{-1}$ and the other bellow the glazed has an U=0,59 $W.m^{-2}.k^{-1}$. The glazed composed with double clear glass with 6mm thick and an air gap with 12 mm with aluminum frame with thermal cut has an U_w=3,46 $W.m^{-2}.k^{-1}$. In terms of energy storage in the construction materials, the ceiling can store 3,72kWh/ºC and the roof 4,87kWh/ºC.

Due to this, the building presents a high thermal inertia. Note that the glass has the lower thermal

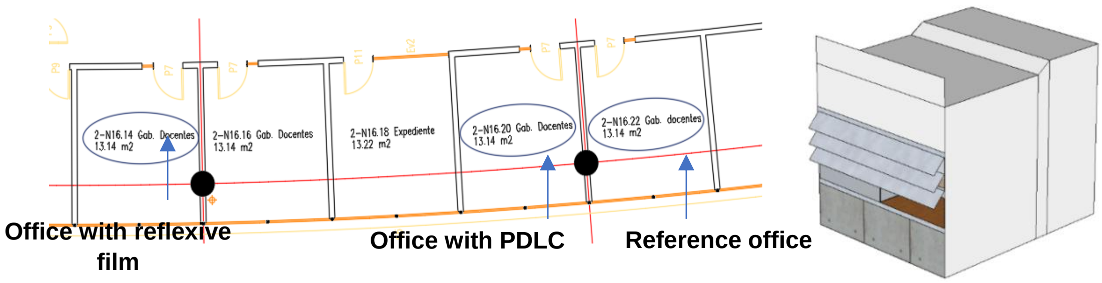

Figure 1-a) office rooms in study and films located; 3D office room geometry

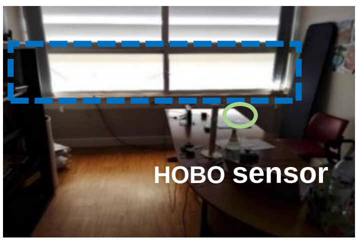

Figure 2- PDLC opaque film

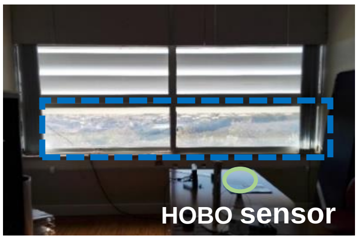

Figure 3- PDLC transparent

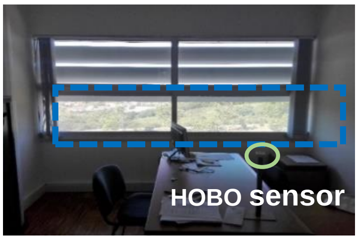

Figure 4- Reflexive film with solar protection

inertia value, so it means that this component cannot storage energy ($\approx 0\text{kWh}/℃$) due to its density and specific heat reacting more easily to temperature differences. The office air change rate was also calculated, applying the CO_2 concentration decay method representing 0,301h^{-1}air change.

2.2 Applied films and methodology

In the glazed façade there are exterior shading blades which remained totally closed to minimize the radiation entry by the remaining glazed area. SmartCling™ Selft Adhesive Smart tint (PDLC) (figure 2 and 3) and adhesive film Deco UV Reflexive film Safe- Linea Hogar with solar protection (figure 4) were used and implemented in two office rooms, in the 50% existing glasses with an area 1,752 m^2 as shown in the previous figures.

This PDLC smart film has $5 \times 10^{-3}\,m$ of thickness, a solar factor (g) of 0,1 for $\lambda = 950\text{mm}$ total light transmittance of 90±1 % and 4±2 % for state on (transparent) and state off (opaque) respectively, an UV block of >99% and IR block >90%, a haze of 4,0±1 % (on) and 85±2 %(off), an operating voltage of 35-75 V AC, a power consumption of 3-4 W/m^2, a switching speed of 50-100 ms for off to on state operation and 200-300 ms for on to off state operation and an operation temperature around -10ºC ~ 60ºC.

Reflexive film with solar protection is composed by 100% PET, had $75 \times 10^{-6} m$ of thickness, a UV block of 92%, IV block 35% and metal reflection of 8%.

To evaluate the thermal comfort, inside office temperature were monitored by using three data loggers HOBO U12-011 Temp/RH with an accuracy of $\pm$ 0,35ºC for temperature and $\pm$3% for relative humidity and measurements with a time frame of 15 minutes, and the external irradiance and temperature were obtained using the meteorological station (Davis Vantage Pro2) installed on the building top. A thermographic camera Milwaukee®, model M12™ 160 X 120 Thermal Imager Kit was used to take thermographic glazed images.

To evaluate visual comfort, luximeter Vici model LX 1332B with an accuracy of $\pm$4% was used to obtain the illuminance in the offices. Several configurations were applied during the experimental procedure: external shading blades, windows and doors are totally closed, and HVAC system and artificial light were off.

To analyze the experimental results, thermal comfort was evaluated with the comfort zone recommended by ASHRAE STANDART 55-2017 and visual comfort according with ISO 8995 (2002).

2.3 Description of 4 situations

2.3.1 Reflexive film and PDLC impact in thermal comfort

In terms of thermal comfort, inside temperature were analyzed according to the external irradiance (G), and thermographic images were captured to justify the results. The first situation evaluates the inside temperature and relative humidity (HR%) in the office rooms by the implementation opaque PDLC and reflexive film in glasses and comparing with the reference office. The second one evaluates the same variables and the same comparisons, but for transparent PDLC.

The data loggers HOBO U12-011 Temp/RH were placed on the desk located at the same height as the hypothalamus as shown in images

2, 3 and 4. Note that hypothalamus is the brain region responsible for temperature regulation.

These situations were performed on two separate weekends to ensure that configurations were respected.

2.3.2 Reflexive film and PDLC impact in visual comfort

The visual comfort is also extremely important because the excess light in workplace can cause discomfort and lower yield. In this sense two zones were created, present in figure 5, ZJ and ZT. ZJ located next to glazing window with a 17 cm perpendicular distance composed by 5 measuring points (1,2,3,4,5) along its length and the main objective of this zone is to understand the films impact on the amount of transmitted light passing through the glazing. ZT located in the work occupant zone, composed by 3 measurements (a,b,c) aiming to understand the behavior of the amount of light as it increases the glazing distance, that is, in terms of office rooms depth, as well as the illuminance is in accordance with recommended values (ISO 8995 (2002)).

Figure 5- Office rooms and the two zones created (ZJ and ZT).

For this evaluation were also created two situations. As we know there are two types of radiation, direct or diffuse. For this case study, was considered essentially direct radiation for clean sky and essentially diffuse radiation for sky with clouds.

In this way, were selected two specific days, with essentially direct (3ª situation) and diffuse radiation (4ª situation), for a specific hour where the radiation entrance was perpendicular to the glazing and registered illuminance values, with luximeter, for ZJ and ZT in 3 office rooms to obtain this illuminance in the reference office. The office with reflexive film and the office with smart film. In this latter, were registered values for PDLC in state on and state off. All the values were withdrawn at a height of 0,73 cm that correspond at the work height occupant.

3 Results and discussion

3.1 Reflexive film and PDLC impact in thermal comfort

In two situations were verified that a delay occurs between the peak solar radiation and the maximum temperatures inside office rooms that can be explained by the high office’s thermal inertia. During the day, the constructions materials absorb and store energy and during the night release this energy to the interior environment. This is also the justification for the variation of temperature to not be as considerable when compared to the external temperature and also that the solar heat gain is the main responsible for the increase of indoors temperature.

In the first situation, relative humidity obtained was between 35-55% and according to this variable and inside temperatures, thermal comfort can be evaluated by using the Ashare Standart 55-2017 humidity and temperature graph.

From these values was verified that reference office room was inside the thermal comfort zone. The others with films, during the first hours with irradiance or during the night were slightly below the thermal comfort. When the inside temperature is lower, more precisely reflexive film office room, that presents more unstable variations.

In this situation, as can been seen in figure 6, compared with the reference office, which always had a higher temperature than the others, office room with reflexive film, allowed a maximum decrease of -0,972ºC at 8:47AM on 9/30/2017 (I) and -0,585ºC at 7:47AM on 1/10/2017 (II). The PDLC opaque also allows a decrease in relatively close hours of -0,493ºC (I) for the first day and -0,3ºC (II) for last day.

In the first day with a mean irradiance of 366W/m^2 an exterior mean temperature of 19,9ºC the films used allowed a mean reduction of -2,2% (-0,56ºC) and -1,5% (-0,4ºC) with reflexive and smart film opaque use comparing with the reference office room. In the last experimental day with a slightly higher mean irradiance (G=379 W/m^2) and an exterior mean temperature of 24,03ºC in reflexive film office obtained an average reduction of -1,4% (-0,37ºC) and in smart film office -0,9% (-0,23ºC). During the daytime in this situation, where (G≠0W/m^2) reflexive film allowed to reach a reduction of -0,46ºC inside room temperature and PDLC opaque -0,31ºC.

In the last situation performed for thermal comfort analysis, was found that, inside office rooms temperatures and relative humidity were inside the thermal comfort. Inside the reference office, the temperature was also higher than the others. Note that the in the previous situation, exterior environmental conditions were different.

In this situation the mean irradiance was 391,81W/m^2 and 371,71 W/m^2 for the first day (07/10/2017) and last day (08/10/2017) respectively and the mean, maximum and minimum external temperature were 24,08ºC, 33,6ºC and 18,5ºC respectively.

Throughout the performance analysis, comparing again with reference office

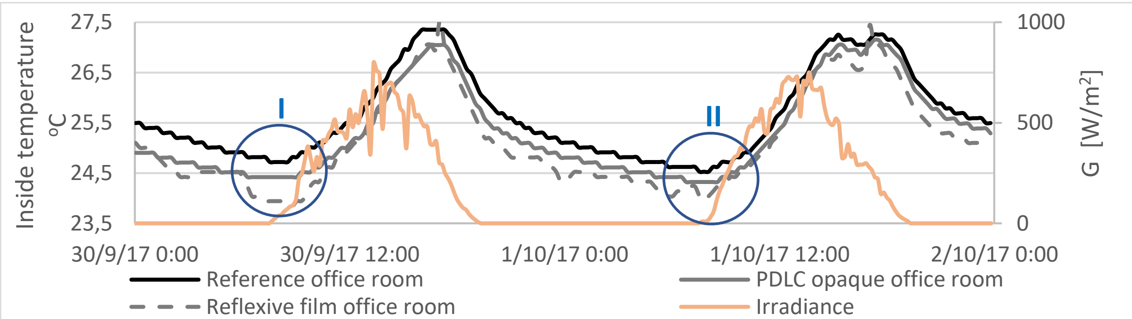

Figure 6- Office rooms inside temperature (Reference, with PDLC opaque and with reflexive film and external irradiance

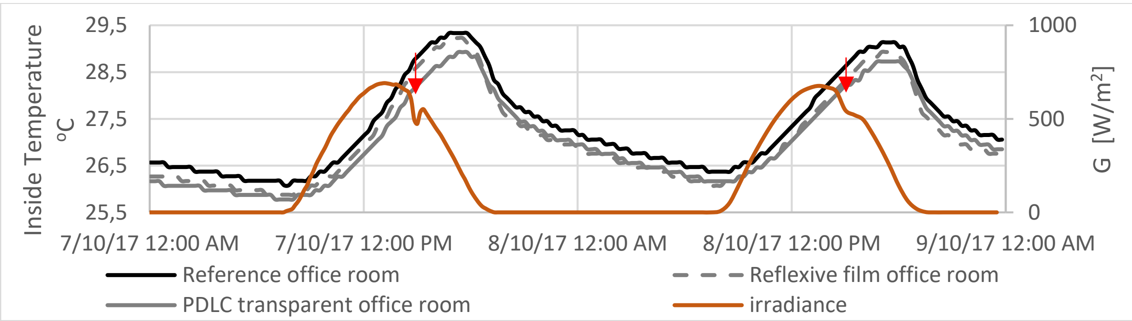

Figure 7- Office rooms inside temperature (Reference, with PDLC transparent and with reflexive film and external irradiance

temperature, office with PDLC transparent film has shown a maximum temperature decrease of -0,61ºC, verified at the hour where the maximum perpendicularity of solar rays occurs with the glazed façade in both days as evidenced in figure 7. In the office with reflexive film allowed a maximum reduction of -0,51 ºC.

During the daytime for this situation, where (G≠0 W/m^2), reflexive film allowed an average reduction of -0,24ºC of the inside room temperature and PDLC opaque allowed an average decrease of -0,39ºC.

According to the values of relative humidity registered in the office rooms in previous situations (30-55%) and according with the thermal comfort zone established for summer time in office environments, a set point T=27ºC was established, for office rooms cooling needs. In the first situation, the reference office would require an additional 4,5 hours of cooling needs, and for the second one, an additional 6,5 hours comparing with the remaining offices. So, it is concluded that the films used promoted a lower cooling need.

Due to film properties, and by its different composition, films cannot be compared between them, although reflexive film thickness were very slow ($75 \times 10^{-6} m$) in comparison with PDLC smart film. That means that, the glass heat transfer coefficient does not suffer any significant changes. On the other hand, with a PDLC film with $5 \times 10^{-3} m$ thickness it will. Even if the conductivity is unknown, this thickness will improve the U value.

Due to their UV and IR block, PDCL presents a better indicate fabricants value, although not always PDLC film presents a lower temperature than reflexive film.

3.2 Reflexive film and PDLC impact in visual comfort

It is generally found that in ZJ the illuminance values are very high, due the illuminance registered being predominantly direct, but when glazing distances increase (ZT) these values decrease by shadding effect (figure 8).

For a better perception the results presented were analyzed based on those obtained in the reference office to understand the influence of the implementation films with the amount of light that crosses the glazing.

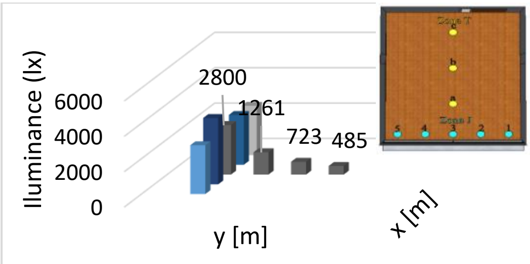

Figure 8- Illuminance in ZJ and ZT in reference office room with direct radiation.

In figure 9, the impact films in illuminance are present. By its analysis it is verified that in ZJ when in the presence of direct radiation, reflexive film enables a decrease in the average illuminance in -12,6 %, but PDLC utilization increases considerably this value. In PDLC state off, despite its low total light transmittance $\tau = 4 \pm 2\%$, this film is characterized by crystals misalignment that scatter the incidence light, however this effect is also sensed inside the office room due to diffuse light passing through it. Although total light transmittance is higher in state on $\tau = 90 \pm 1\%$, an electric field actions crystals alignment, allowing the passage of light, essentiality direct light but also there are a percentage of diffuse light causing its increase. These obtained results support the previous results obtained with the same type of smart windows when the solar spectrum was analyzed. [4]. When in presence of diffuse radiation, the PDLC promotes a decrease in average illuminance, better than reflexive film. Reflexive film can decrease its value in -8,9% and the PDLC can decrease in -35,3% and -15,8% for its state's operation off and on respectively. Note that, due to its lower total light transmittance, PDLC in opaque state has a reduction capacity of -19,5% comparatively with transparent state.

In the ZT considered as a workplace zone and for visual comfort analysis, it is important to understand that the average illuminance (Em [lx]) and uniformity illuminance are in accordance with the ISO.

In figure 9 it is possible to understand that with essentially direct radiation present, PDLC film in transparent or opaque states contributes for an illuminance reduction in -21,1% and -25,1% respectively and reflexive film contributes, although with low percentage, an increase of 1,6%. With diffuse radiation, reflexive film continues to contribute with an increase of illuminance and PDLC also allows a decrease in the average illuminance when in opaque state. Note that, PDLC in state on (transparent) contributes an average increase around 9,2%.

Although the increase and the decrease comparison levels are important, these values must be according with the ISO for visual comfort. According with ISO 8995 (2002) for writing, reading and processing data tasks in office, Em should be 500 [lx], and the illuminance uniformity should be ≥ 0,7 and can be calculated by equation 1

$$Illuminance\ Uniformity = E_{min} / E_{average} \quad (1)$$

According with the recommended value within the presence of direct radiation only, although higher than 500 lx, PDLC smart film can improve this value. In presence of diffuse radiation, reference office can offer a value slightly above than recommended. In this type of radiation, PDLC in state on offers a value slightly above than recommended and PDLC in state off is slightly below 448lx. Although, being natural lighting, the occupant adapts more easily to this value than if it were artificial light.

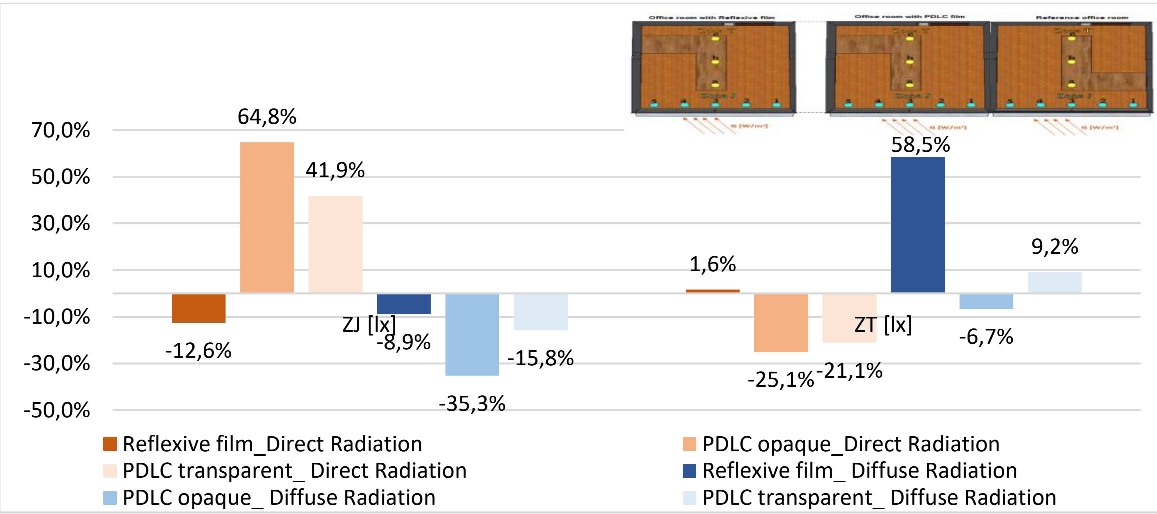

Figure 9- Effect in average illuminance by using reflexive film and PDLC smart film- Reference office room comparison

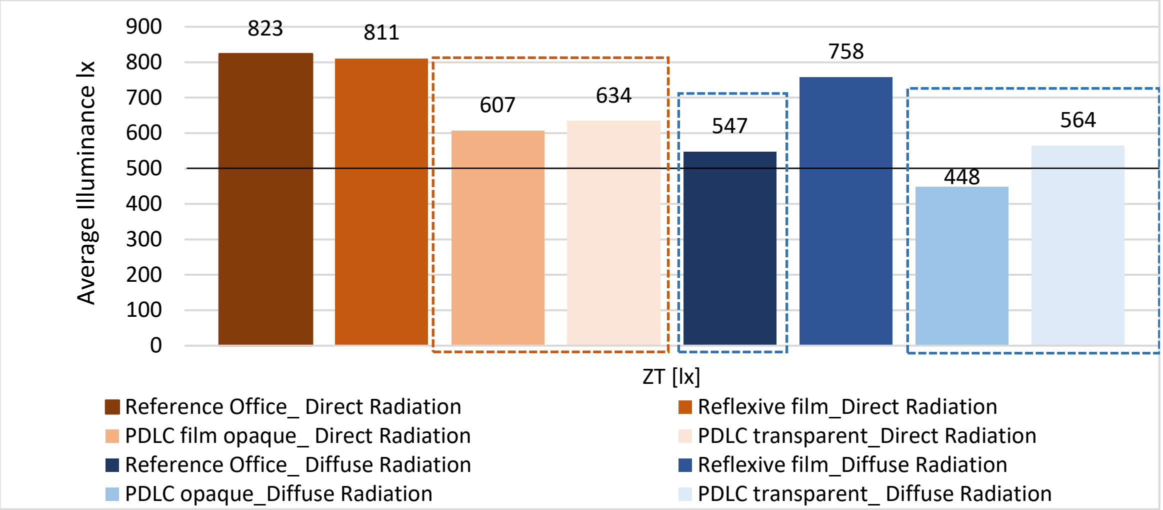

Figure 10- Average illuminance for ZT (work zone) in reference office room, office room with PDLC in opaque and transparent and in office room with reflexive film.

4. Conclusion

Smart films have optical properties that allow the reduction associated with cooling and heating needs, as well as its costs. This is due to their transmittance change and therefore entrance solar gains. Although the optical properties of the final combination, double glass with smart film or with reflexive films were not calculated, and due to their different optical properties, the used films cannot be compared between them. It cannot be confirmed if one film is better that the other, therefore, this conclusion is focused on the obtained experimental results.

In terms of thermal comfort, films promote an improvement in interior temperature, but in a lower value (ΔT>-1ºC). During the daytime period, there were reductions in terms of mean temperature. Compared to the reference office room by using reflective film temperature can reduce -0,24ºC and -0,46ºC for both situations (3rd and 4th situation) and using smart film there was a mean reduction of -0,31ºC when was opaque and -0,39ºC with transparent. The difference of temperature obtained in the office rooms with films compared with reference office temperature has shown results that are sometimes slightly similar with the error hobo sensor. Although the hobo sensors have been calibrated, there are no guarantees that these sensors have not suffered a de-calibration and, the applied films were not applied totally in contact with the glass surface. Although greatly reduced, there is an air gap, that may have promoted the increases of temperature. In general, temperature differences are not significant, but films were only implemented in 37,76% of the glass façade.

However, in terms of visual comfort, the intelligent film impact and reflexive film is most evident. PDLC film due to its transmittance change, allows an improvement in the interior visual comfort, despite the significant increase of illuminance in the ZJ. When in the presence of direct radiation, due to light scattering effects it presents significant illuminance improvements in the work zone of -26,2% in opaque mode and -23% in transparent mode allowing an approximation of the recommended value for the type of space and activity (500 lx), as well as providing a better distribution of light in the interior space and a decrease in the shading effects. When in the presence of essentially diffuse radiation, the intelligent film enables a significant reduction in the ZJ considered comparatively to the reference office room either in the opaque or transparent mode. Although the office room without any film applied on the glazing does not present significant illumination problems in the working zone, since it is slightly above the recommended value (+ 9,4%), the intelligent film can adjust this value by the transmittance variation. Although reflexive film does not allow for significant improvements in visual comfort, the intelligent film provides better illumination uniformity compared to the reference office room.

Although in all the literature it is verified that this type of intelligent film (PDLC) is more directed for privacy use, the experimental analysis concludes that it presents advantages mainly in terms of visual occupant comfort.

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