ROOF DESIGN AND SKYLIGHTS EFFECTS ON THE ENERGY PERFORMANCE AND COMFORT OF LOW ENERGY INDUSTRIAL BUILDINGS

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Abstract

In industrial or commercial buildings, the roof design and its opening systems are essential toward the thermal and lighting performance. Usually, roof coatings are designed to maintain waterproofing while the smoke evacuation is partially or totally ensured by the skylights installation. Yet, these components participate in increasing/decreasing roofs solar reflection, daylighting and may improve natural ventilation under operative conditions and passive cooling. The presence of these openings and the consideration of roofs solar reflectance studied here have a direct impact on the overall building thermal behavior. Indeed, the combination of solar gains and thermal losses depends on the design parameters (solar reflectance, opening size, etc.), climate and the season conditions. The objective of this study is to assess the impacts of skylights and solar reflectance on building energy consumption, comfort and daylight factor through annual simulations. Coupled heat and mass transfer is computed using the coupled codes TRNSYS and CONTAM. In parallel, lighting simulation is performed using DIALux. Coupling the heat and mass transfer and lighting simulations is realized through daylight factors that determine the appropriate artificial lighting to be considered in the calculation procedure. The results are analyzed and discussed considering the parameters. The advantages of combined use of skylights and highly reflective roofs are detailed considering both of overall energy consumption and summer comfort.

KEYWORDS: solar reflectance; skylight; cool roofs; coupled heat, air and lighting simulation; daylighting.

1. Introduction

In the case of industrial and commercial buildings characterized by large areas of roofing, heat exchanges at the roof are very important. In summer, the high thermal insulation of the envelope of low energy buildings and their high air tightness result in overheating (Langmans et al. 2010). As such, the use of passive cooling techniques such as cool roofs and night natural ventilation through skylights can be a good solution for this type of buildings(Bahadori & Haghighat 1985; Breesch et al. 2005; Levinson & Akbari 2009; Muselli 2010).

The introduction of cool coatings and openable skylights can have beneficial or negative impacts on the building thermal behavior (Trabelsi et al. 2010). Indeed, their presence plays an important role in solar gain and heat loss; this has repercussions in terms of building energy performance and thermal comfort. Depending on the season, these aspects (heat and air balance) may have different impacts. In winter, we try to limit heat loss (conduction in the walls, convection, longwave radiation and ventilation) while maximizing solar heat gain (shortwave radiation). The aim is to reduce the energy consumption of the building (in term of heating) and to maintain a certain level of thermal comfort. In summer, we attempt to cool the building by removing the maximum amount of heat (conduction in the walls, convection, longwave radiation and ventilation) while minimizing solar gain. The objective is to reduce the energy consumption of the building (in term of air conditioning) or in the absence of active system, to maintain a certain level of thermal comfort in summer. These two objectives often lead to conflicting solutions hence the existence of optimal behavior.

In this context, the study that we conducted concerns industrial or commercial buildings that are fitted with cool coating and openable skylights. Thus, the potential of natural ventilation is increased and the use of artificial lighting can be reduced. In this work, the assessment of the impact of solar reflectance and skylights on building energy consumption, comfort and daylighting is achieved.

2. Model

The study is carried out on two floors commercial building located in Poitiers (France) made of steel structure. The building is constituted by offices in the south part and a store in the north part (Figure 1). The thermal insulation consists of mineral wool; it is about 150 mm thickness for the store, 250 mm for offices and 280 mm for the roof. The thermal inertia of the building is mainly related to concrete slabs (160 mm thickness in ground floor and 120 mm in top floor). 45% of the frontage of the offices part is glazed with solar protections; store and meeting room (1st floor) are fitted with skylights (4.5 % of the roof area concerning the store). The offices part and the store area are provided with independent mechanical ventilation systems. The building has no air conditioning system and the cooling is achieved by night ventilation through openings in the roof.

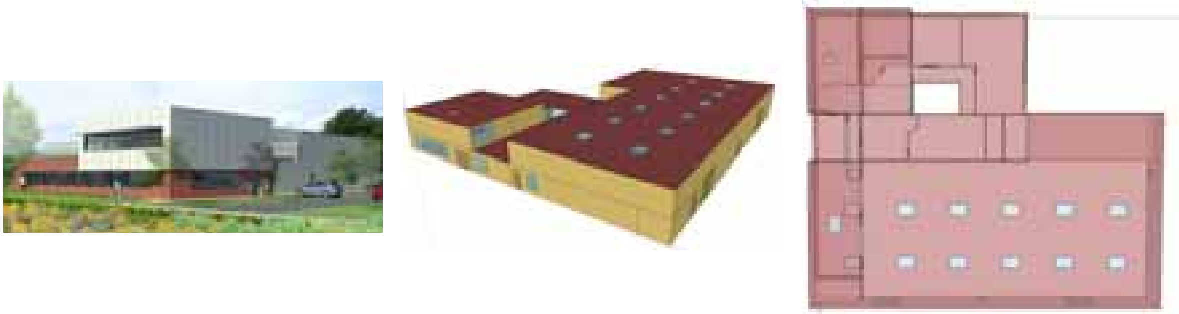

Figure 1: Plan of the studied building

In this paper, a multizone nodal approach has been followed because it is the most suitable for our case. Indeed, the objective of the study is to evaluate building behaviour over a whole year including several physical phenomena and aspects such as radiation transfer, interaction between building and heating system... Heat and air simulations have been achieved using the coupled codes TRNSYS and CONTAM. These codes are widely used by the scientific community (Beckman et al. 1994; Chel et al. 2008; Sowa & Karas 2007).

3. Results and discussion

3.1 Comparison of passive cooling solutions

The studied building is often found in the service sector with two parts (offices and store). The management of heating in this type of configuration is particular. Indeed, heat and air transfer simulations show that the maximum heating power to be installed is located in the store (large volume) with 10% of the total power estimated at 31.5 kW. The maximum annual energy consumption is in the office part with 32% of total energy consumption estimated at 8.6 kWh /m².year. This feature is explained by the fact that the level of heating for these areas is not the same. In addition, the store being provided with skylights, it benefits from solar gain regardless of the orientation.

In summer, in order to estimate the thermal discomfort problems during the occupation periods, we considered the “PPD” index (predicted percent of dissatisfied people) and the rate of discomfort defined by the occurrence of indoor temperatures above 26°C. The mean rate of discomfort during occupation is about 74% over the period of summer with temperatures ranging between 22.5 and 31.2°C for the store zone. According to Figure 2, for such kind of building (high thermal insulation and high air tightness), it exist a high risk of discomfort whatever the use of the zone. For example, the PPD index ranges between 30 and 100% during 39% of occupation time in the store zone.

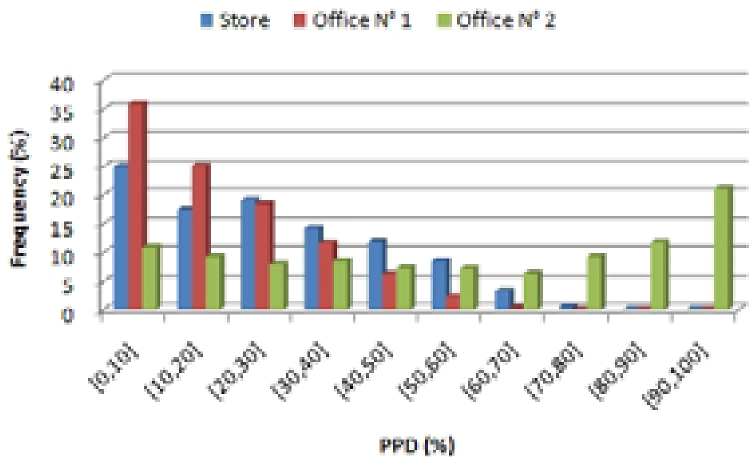

Figure 2: Frequency of occurrence of PPD index during the period of occupation

In the absence of air conditioning system, to have recourse to night natural ventilation and high-albedo coating can be a solution for this type of building. To demonstrate the relevance of the use of passive cooling techniques cited above for this type of construction, heat and air transfer simulations were performed considering several scenarios as shown in Table 1.

Table 1: Studied scenarios

Scenario	Description
Stand.	Standard case: No passive cooling technique is considered
Sol. 1	Solution 1: Cool Roof (solar reflectivity = 0.8 ; emissivity = 0.9)
Sol. 2	Solution 2: Night Natural Ventilation through skylights
Sol. 1+2	Combination between solution 1 and Solution 2

The use of cool roofs coatings provides a better thermal comfort in summer and reduces heat island effects. Indeed, they reduce the roof surface temperature Therefore, they reduce cooling demand and associated additional heat releases. In addition, it improves the durability of the materials constituting the wall by minimizing temperature gradients between the inner and outer surface. To assess the impact of albedo on the thermal behavior of the store zone, we performed heat transfer simulations on our case study by considering two values of solar reflectivity (0.2 and 0.8).

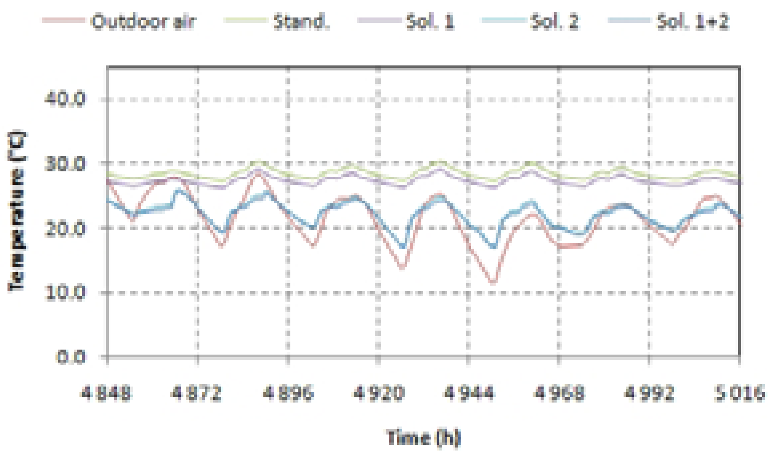

Figure 3: Evolution of operative temperature in the store zone for the different studied scenarios

The use of openable skylights increases the surface for ventilation and thus potentially increases the air flow due to natural ventilation and particularly thermal buoyancy. To show the impact of the use of night natural ventilation to solve the problems of summer discomfort, we conducted heat and air transfer simulations considering closed and open positions of skylights at night.

Figure 3 shows the evolution in time of the operative temperature in the store zone during a week of July for the different studied cases shown in Table 1. From this figure we see that actually, the building is in a discomfort situation for the occupants. Indeed, in the standard case, the average temperature of the store zone is about 27.3°C even though it is about 19.28°C for the outdoor air temperature. Although a week of relatively cool, for such building, it is really hard to dissipate the entropic and solar heats stored during the day.

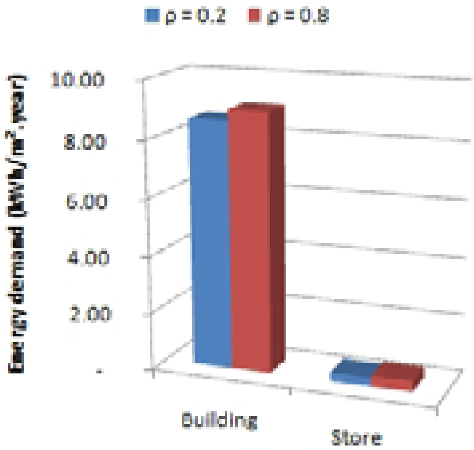

Figure 4: Energy demand for standard (ρ=0.2) and cool roof (ρ=0.8)

The use of a high albedo coating (Sol. 1) does not significantly modify the thermal behavior of the building. In one hand, the increase of a solar reflectivity from 0.2 to 0.8 causes an increase in the annual consumption for heating of 4.4% (Figure 4). In the other hand, it causes a decrease in the mean temperature of 1.2°C (Figure 2) and a decrease in the mean rate of discomfort during the period of occupation of 16%. Despite a drop of 1.2°C in temperature, the building remains in a discomfort situation for the occupants.

As a reminder, the use of cool roof has a direct impact on surface temperature with a potential reduction of about 13°C on average (Bozonnet & Doya 2010). This temperature reduction can have a significant role on the inside air temperature only if the thermal insulation of the roof is low which is not the case for the typology of the building studied. However, with the noticed reduction in room temperature, one can easily imagine the gains in terms of energy in the case of air-conditioned buildings.

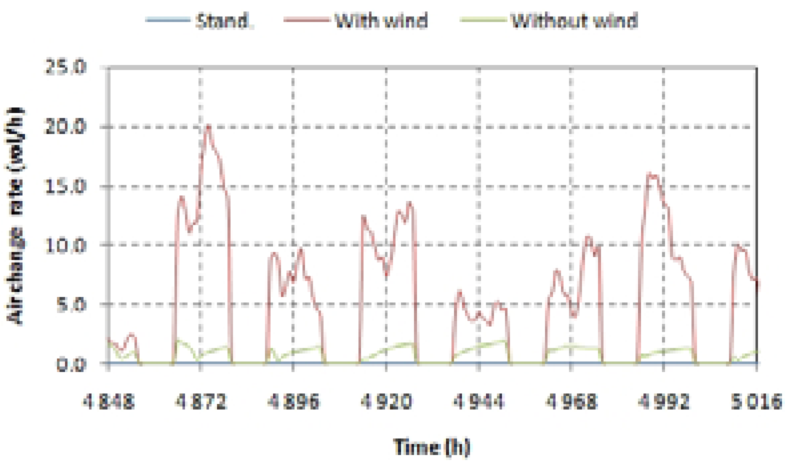

Figure 5: Air change in the store with and without wind

The use of night natural ventilation through skylights for passive cooling (Sol. 2) is a good solution to address the problem of summer discomfort in the studied case. Indeed, the average operative temperature increases from 27.3°C in the standard case to 20.6°C in the case with night natural ventilation. Then, the maximum temperature is about 25.7°C (Figure 2). As we come to deal with the problem of overheating in summer with night natural ventilation only, the use of both techniques (Sol. 1+2) does not materially alter the evolution of operative temperature in this case. The effect of the cool roof on operative temperature is clearly identifiable from a given temperature threshold.

The potential of night cooling by natural ventilation depends on both the temperature difference between inside and outside and the wind speed. The results presented above were obtained by considering the speed and wind direction from the meteorological databases. Yet, they are closely related to the typology of the urban site. To override the site conditions, we consider the air change due only to the effect of thermal buoyancy. Figure 5 shows the air change rate in the store zone in the cases of zero and non-zero wind velocity and Figure 6 shows the evolution of the operative temperatures for the same conditions. Despite a strong decrease in the rate of air (about 5.9 vol/h on average), the operative temperature is acceptable with a rate discomfort of 2.3% only.

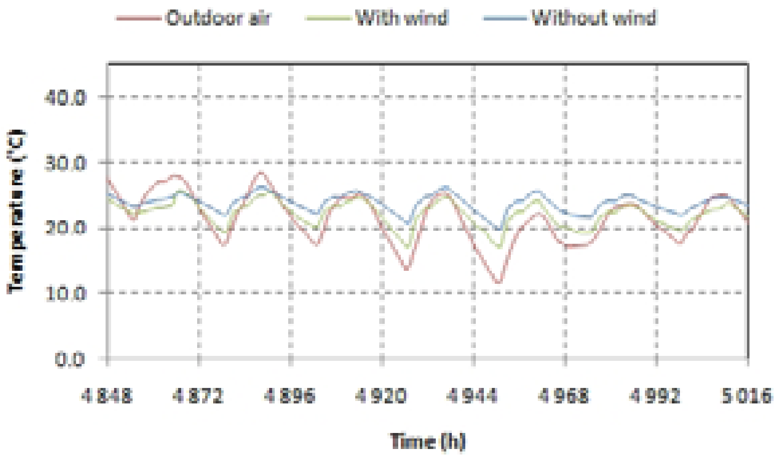

Figure 6: Evolution of operative temperature in the store zone in the cases of zero and non-zero wind velocity

3.2 Natural lighting

To demonstrate the impact of the skylights on the distribution of illuminance level, we conducted a study of natural lighting in the store zone under an overcast sky. This study was performed using the software DIALux©. The latter is well known among specialists and technicians of lighting, because it allows a very photo-realistic approach to the project all keeping the reliability of the results of calculations.

The results of the illuminance at the walls of store are reported in Figure 7. This light level is obtained for a surface of skylight representing 4.5% of the total area of the roof and for a clear sky ofr a typical day of July. Then, the daylight factor (DF) is equal to 0.84 %. Under these conditions, one can very well do without artificial lighting because natural lighting is more than enough for such space. Indeed, the average illuminance on the working plane is about 793 lux. However, in the case of the use of skylights for natural lighting, special care must be taken to avoid glare (direct or by reflection) and the visual appearance of stains on the floor. To remedy this problem, a more uniform distribution of skylights may be considered.

The good level of illumination on the working plane suggests energy savings on artificial lighting. This requires the control of the latter depending on the DF and the light level outside. For the rest of the study, we use artificial lighting only if the average illuminance on the working plane due to the natural light does not exceed the minimum recommended by the regulations. Then, average illuminance on the working plane is calculated in a simplified way by multiplying the DF by the outdoor illumination on a horizontal surface obtained from meteorological databases.

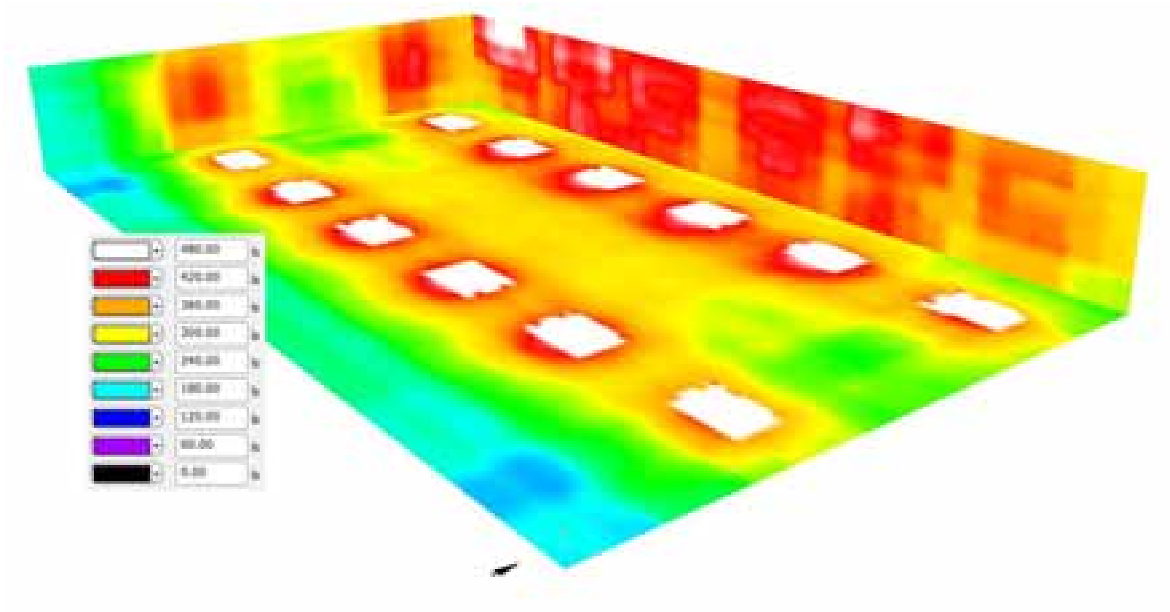

Figure 7: Distribution of illuminance on the inner walls of the store zone

3.3 Parametrical study

For a hot climate, (Hassouneh et al. 2010) have conducted thermal simulations of a residential building with a glass surface facing the south and for different types of glazing. The increase in glass area saves heating energy, whatever the type of glass, and is enhanced for low emissivity glass. In addition, the control of lighting induces a reduction of peak cooling load for each month (Andersson et al. 1987; Li et al. 2005). The impact of translucent on energy consumption is also reflected through the savings on artificial lighting (Chel et al. 2010). The impact of the use of translucent on lighting and heating depends on the glass surface, exposure and solar gain. Here after, a parametric study on the influence of the surface of skylights on the building heat and air behavior and lighting is presented.

To illustrate the impact of the skylights, we performed simulations on the case study presented above where we considered four skylights surfaces: 4.5 - 9 - 18 and 36% of the total area of the roof. The increase in the surface of the openable skylights can of course increase the air change rate but in the same time it generates an increase in operative temperature as shown in Figure 8. Increasing skylights area from 4.5 % to 36%, air change rate go from 1.4 vol/h to 1.86 vol/h on average. In addition, the level of discomfort is increased from 0.3% to 84% as shown in Figure 10.

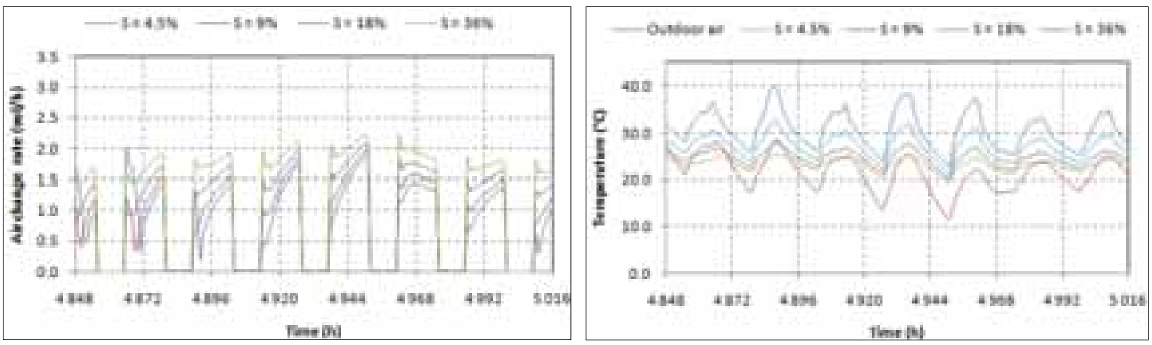

Figure 8: Effect of skylights surface on air change rate and operative temperature in store zone

The increase in the surface of skylights creates a greater solar absorption in the interior of the building that tends to overheat the atmosphere inside. The stored heat cannot be removed by simple natural ventilation at night. As the temperature level increases, the use of cool roof can cool the interior ambience air.

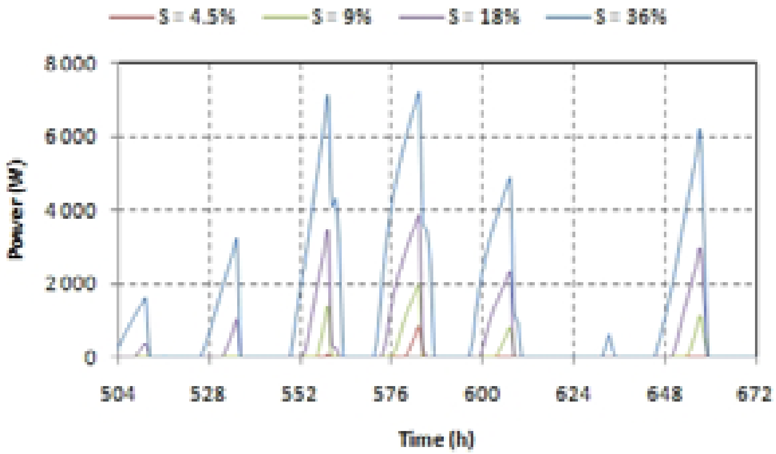

Figure 9: Evolution of heating peak load during a winter week

According to Figure 10, annual energy consumption for heating decreases by 2.6% due to the solar gain and then increase as the solar gains do not offset losses due to heat transmission at the skylight. However, the peak heating power increases continuously due to small solar gain during winter (Figure 9).

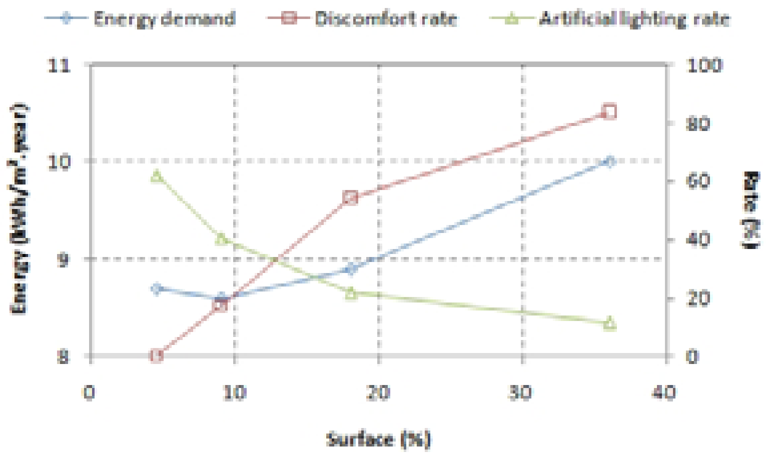

Figure 10: Effect of skylights surface on energy demand, discomfort rate and artificial lighting rate

The increase in the surface of skylights plays a role also in the level of lighting inside the building. Increasing the surface of the skylights increase four times the DF, it is then equal to 6.72% for skylights roof coverage of 36%. Also, it is noticed that a marked decrease in the use of artificial lighting from 62.1% of the time during occupancy to 11.7%.

In this article, comparisons had often been presented as relative difference. The fact is, given that we are dealing with a low energy building, the annual energy demand for heating in absolute value never exceeds 11 kWh / m².year which is quite small. In addition there is an optimum of skylights coverage between 9% and 18%. This optimum also depends on the roof reflectance, the roof thermal resistance and the special considerations to avoid glare.

4. Conclusion

In this paper, we studied the impact of openable skylights and roof's albedo on a low energy office building through a parametrical study. It concerns the surface of skylights and roof albedo parameters. The increase in the number of skylights will reduce the artificial lighting time. The natural ventilation during the night through the skylight has a better potential to refresh then the use of high albedo roofs up to a certain threshold. Beyond, the annual heating energy consumption becomes very important. Nevertheless, an optimum exists for skylights coverage between 9 and 18%.

To complete this study on the potential for passive cooling using cool roof and natural ventilation through the skylights at night, a further parametric study is needed. It will also include the thermal resistance of the roof and the type of climate. Finally, thermal stratification large volumes zones must be modeled which would change the levels of discomfort in this study.

The authors thank Region Alsace for their financial support.

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