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A case study on energy consumption and overheating for a UK industrial building with rooflights

Xiaoxin Wang *, Christopher Kendrick, Raymond Ogden, Nicholas Walliman, Bousmaha Baiche

School of Architecture, Oxford Brookes University, Oxford OX3 0BP, UK

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ABSTRACT

Rooflights have become the common installations for industrial buildings to meet both the human health requirements for natural light and the need to save artificial lighting energy, especially for retail or distribution sheds that have big roof to floor area ratios and limitations of using glazing on side elevations. Since almost all of these buildings normally operate during daytime, an opportunity exists to save lighting energy by fitting automatic artificial lighting control. However, due to solar gains through the rooflights, the buildings are vulnerable to summer overheating. If overheating occurs regularly or over sustained periods, it will lead to the need for mechanical cooling, which inevitably results in more operational energy consumption in addition to the initial installation cost. To remedy this potential problem, natural ventilation through ridge openings is explored in this paper because it consumes almost no extra operational energy. Thermal modelling is therefore implemented with focus on influences of lighting control on energy consumption and effects of natural ventilation on reducing overheating. The modelling results indicate that lighting control can save lighting energy by 70% and the use of both ridge ventilation and lighting control can reduce overheating hours considerably, as internal heat is dissipated through the ridge openings and lighting heat gains are cut. In addition, converted from lighting and heating energy used, the overall CO_2 reduction can reach 45% when both lighting control and ridge ventilation are applied. The findings from the study would encourage the use of rooflights for industrial buildings and would provide guidance on how to save operational energy while ensuring the thermal comfort inside the buildings.

1. Introduction

Natural light is a practical requirement for workplace which is required by health, safety and welfare regulations [1]. To comply with this, building designers commonly use rooflights as a solution for industrial and commercial buildings [2], especially retail or distribution sheds. Another advantage of using natural light is to save artificial lighting energy consumption with the help of automatic lighting control. This is very important because currently global warming is believed to be directly associated with energy consumptions. Greenhouse gas emissions, principally carbon dioxide (CO_2) resulting from burning of fossil fuels, can significantly alter the Earth's climate by intensifying the global warming [3]. Buildings in UK account for 46% of total carbon emissions [4], and therefore it is in the building sector that the greatest savings of operational energy should be made. The electricity consumption of artificial lighting in buildings is a major contributor to building total CO_2 emissions, estimated at greater than 20% of the total building energy consumption [5]. Therefore, the use of daylight as the primary light source in buildings during daytime is of great interest to those concerned with energy conservation because it potentially minimises the consumption of electricity for artificial lighting [6–8]. Obviously, automatic lighting control can be used as a way of automatically reducing or eliminating the amount of electric lighting required when there is an adequate contribution of daylight for a working space. However, due to global warming exacerbating overheating inside buildings [9–11], those with rooflights in particular are vulnerable and can potentially become overheated. Of course, these buildings should be designed not only to save total energy consumption which leads to less CO_2 emissions but also to minimise overheating to ensure thermal comfort. The solution to the former would be lighting control and to the latter, natural ventilation. In this paper, ridge ventilation is seen to be an effective way to cope with overheating in summer, without bringing in much extra energy consumption.

For an automatic on/off lighting control, a photocell component installed in the building measures daylight levels, transmits the data to the control component, which then simply switches the

* Corresponding author. Address: Oxford Institute for Sustainable Development, Oxford Brookes University, Oxford OX3 0BP, UK.

E-mail address: xiaoxin.wang@brookes.ac.uk (X. Wang).

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artificial lighting on or off. Overall, lighting can be automatically regulated and the lighting designs are adapted to the uses and surroundings of the working environment, and if desired, the settings can be overruled according to personal preference through a push button or remote control [12–14]. Lighting control systems, with their great potential of energy savings, have been investigated widely, especially when applied in office buildings [7,15–21]. The approaches were mostly accomplished by modelling, such as using ESP-r [15], Radiance [17], DOE-2.1E [18], Relux Vision [19], DAYSIM [20] and others, upon which the energy savings were calculated as a result of changes to the lighting and daylighting specifications of the building. Daylit corridors and atria [12,22] are other suitable places to use lighting control systems because lighting levels inside the spaces are strongly dependent on the daylight availability. Dubois and Blomsterberg [23] reviewed actual energy use for office lighting, and energy saving potentials for future low energy office buildings in north Europe, and detailed strategies to reduce energy use for lighting, claiming that 40% energy savings can be achieved if energy efficient lightings were used and further 40% savings would be reached in terms of lighting control through on/off or dimming. However, almost all of these investigations apply to office buildings or big atria or corridor areas. Only one publication was found that aimed at enhancing human performance by changing the lighting in an industrial workplace [24].

Natural ventilation relies on air pressure difference to supply and remove air through an indoor space by any natural means [25,26]. The amount of ventilation depends critically on the size and placement of openings (such as windows or doors) in the building. With an increased awareness of the cost and environmental impacts of energy use, natural ventilation in buildings has become an increasingly attractive method to reduce energy use and associated costs [27]. It aims at supplying acceptable indoor environmental quality and maintenance of a healthy, comfortable, and productive indoor climate, instead of using the more costly prevailing mechanical ventilation approach. In favourable climates and buildings types, natural ventilation could be used as an alternative to air-conditioning systems, resulting in a reduction of total energy consumption. When natural ventilation is not sufficient on its own, large box fans are often used to enhance air movement.

From a literature survey, little work has been carried out on energy and thermal comfort issues for these industrial buildings with rooflight installations, therefore a study was carried out, as described in this paper, using thermal modelling to quantify the artificial lighting energy savings gained by using automatic lighting control and natural ventilation to combat overheating.

2. Methodology

2.1. Model of the building

The industrial building modelled in this paper is a one-storey portal framed shed with a single ridge pitched hip roof, illustrated in Fig. 1. The total floor area of the building is 2322 m^2, of which the retail area that is modelled in this study is 2200 m^2, because there is a space occupied as an office at the rear of the shed. The height of the shed is 9 m from ground to eaves. Fig. 1 also shows the rooflight arrangement on the roof, which actually takes either 15% or 12% (only 15% as an example shown in Fig. 1) of the floor area of the building. The rooflights are perpendicular to the ridge and parallel to each other, but having different lengths to avoid constructions below, i.e. office at the rear and entrance porch at the front of the building. In addition, there are no rooflights in the hip roofs.

The building is orientated with the entrance porch facing south-west. An air infiltration rate of 0.25 ach is applied in the modelling.

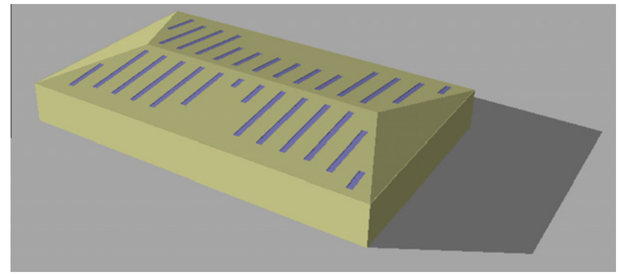

Fig. 1. Three-dimensional model of the building.

Table 1
Elemental *U*-values for the building.

Elements	W/m^2 K
External walls	0.26
Internal walls	0.30
Roof	0.20
Ground floor	0.17
Rooflights	2.80

The building is presumed to operate from 08:00 until 20:00, Mondays–Sundays. Internal gains from occupants are 3.5 W/m^2 sensible and 3.5 W/m^2 latent, while equipment contributes 2.0 W/m^2 gains [28].

The walls and roofs of the building are built using metal cladding panels with elemental *U*-values shown in Table 1, recommended by UK building regulations [29]. The building is only heated in winter, with a set point of 18 °C, and there is no mechanical cooling application in summer. The base case of the study is that the building opens cargo doors, at the rear of the shed, to cool the internal air in summer. A further cooling method by natural ventilation through two ridge openings, with dimensions of 0.2 m × 40 m each, is investigated in this paper to cope with overheating problem.

Although continuous dimming lighting control is proved to be an economic means of energy saving, the on/off lighting control is also deemed to be an efficient energy saving technique from some cases [22,30]. It is known that frequently switching the lights on and off leads to a reduced life of the lamps [31], but automatic on/off lighting control other than dimming lighting control is still adopted in this paper because of its simplicity and therefore being easy to integrate into the modelling. The on/off lighting control works using photocell sensing control equipment, based on the level of daylight availability. The lighting level is set to 500lux [28] with maximum lighting gain of 5.6 W/m^2.

2.2. Principle of daylight analysis

The standards for daylighting analysis should consider daylight availabilities, i.e. daylight uniformity ratios, daylight illumination levels and daylight factors. To maintain lighting levels inside buildings, natural light is normally the prime means of lighting, with electric light to supplement it. Therefore, electric lighting is usually designed with the assumption that there is not sufficient daylight to achieve the desired illumination levels. Roof-lights can substantially reduce electric lighting requirements but will result in an increased heat loss in winter, so that this study compares and analyzes the total energy that is the sum of lighting and heating consumptions altogether.

As discussed above, the most common means of admitting daylight for many industrial buildings is through rooflights, with full guidance on the design and effects of rooflights and windows from