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Optical aspects and energy performance of switchable ethylene-tetrafluoroethylene (ETFE) foil cushions

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HIGHLIGHTS

- Switchable ETFE cushions has been employed in building envelope for daylight and solar heat control.
- Ray-tracing techniques were used to investigate the effects of various design aspects of the ETFE.
- A parametric study was carried out investigating the optical performance of switchable ETFE.
- The impact of switchable ETFE cushions on building performance were studied.

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ABSTRACT

A pneumatic multilayer foil construction with a kinetic shading mechanism has the potential to be an effective response to dynamic climatic factors, such as solar radiation, and therefore moderate the energy consumption of buildings. A parametric study was carried out on a switchable ethylene-tetrafluoroethylene (ETFE) foil cushion with the purpose of investigating the optical performance of an adaptive building envelope and its impact on building energy performance regarding heating, cooling and lighting. Ray-tracing techniques were used to investigate the effects of surface curvature, frit layout and frit properties, on the optical performance of the cushion in open and closed mode. A range of incidence angles for solar radiation were simulated. The results of the simulation showed an angle dependent optical behaviour for both modes. The influence of the dynamic shading mechanism on building energy performance was further evaluated by integrating the optical data obtained for the ETFE foil cushions in a comprehensive energy simulation of a generic atrium building using EnergyPlus. Results suggested that switchable ETFE foil cushions have a higher potential to reduce cooling and heating loads in different climatic regions, compared to conventional glazing solutions (i.e. uncoated double-glazing and reflective double-glazing), while providing good conditions of natural daylighting. Annual energy savings of up to 44.9% were predicted for the switchable ETFE foil cushion in comparison to reflective double glazing. As such, this study provides additional insight into the optical behaviour of multilayer foil constructions and the factors of design and environment that potentially have a major impact on buildings energy performance.

1. Introduction

The building sector currently consumes one third of the global final energy [1–4]. Increasing energy demands for commercial and residential building with an expected growth of up to 1.9%/year [5], raises the necessity for further improvement of the energy performance of buildings. Most of the energy consumed in buildings during their operation and maintenance is for space conditioning (approx. 50%) and lighting (approx. 25%) [6]. The building envelope, which is the interface between the external and internal environment, is, therefore, a crucial element of the building unit [7–9]. It has huge potential to impact the indoor comfort conditions and to improve the overall energy performance of the building by up to 40%, considering only savings in heating and cooling [10–13]. Much attention has been paid, over recent decades, to passive strategies, which aim to maximize the thermal damping effects of the building mass, while increasing insulation of walls and windows, and reducing thermal bridging of building elements [14–16]. However, the general tendency in architectural design moves towards light and transparent structures, such as membrane and foil structures, which offer high flexibility in form and function [17]. Although challenging in terms of energy efficient design, this solution is often adopted for widespan canopies because of its reduced weight and

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resulting cost effectiveness [18]. Recent technological advances in control systems, and miniaturization of sensors and actuators, have made the development of actively adaptable building envelopes possible [19]. Moveable parts and transforming elements are fully integrated into the building system and are able to react instantly to changes of the environment or the user demands [20]. These technologies create great opportunities for the optimization of the thermal and optical performance of the building envelope, and improve the energy efficiency of membrane structures [21]. A case study on the "Gardens by the Bay" project in Singapore evaluated the influence of the dynamic operation of shading screens on the hygro-thermal performance of a dome structure covering a botanical garden. It was found that the retractable textile membranes are able to control the incident solar irradiation on the glass envelope, lower the risks of overheating and reduce cooling loads, while maintaining stable natural lighting conditions for the plants throughout the year [22]. Chiu and Lin [23] evaluated the performance of adaptable pre-tensioned textile membrane structures in façades for multi-storey buildings and found that energy savings of up to 13% were achievable for heating and cooling loads, when compared to conventional static tensioned membranes. Although these results are promising for the development of more energy efficient building envelopes with woven textile membrane materials, few studies have evaluated the potential of adaptable multilayer ethylene tetrafluoroethylene (ETFE) foil constructions. In the past, research has mainly focussed on the structural aspects of ETFE foil constructions, being the most common type a pneumatic structure in the shape of a cushion, which consists of at least two foil layers and is pressurized with air for structural stability. Only recently has the optical and thermal performance of ETFE foil envelopes been addressed in depth in the literature [24–27]. This development, along with the increasing number of built ETFE foil structures, has opened questions about the need for climate adaptive foil systems [28–35]. Due to their light weight (density = 1.75 g/cm^3), material thinness (t = 12–300 µm) and high transmittance (typically, solar = 93%, visible = 90–97% for clear foil), [27,36], ETFE foils present both risks and opportunities for their use in building envelopes. ETFE allows one to build lighter while offering better light transmittance than glass, but uncomfortable conditions such as glare and overheating during the summer season have been reported as potential problems in spaces enclosed by ETFE foil constructions [29,37]. Added functionalities, achieved using novel printing techniques, and inks and material additives with high reflection, absorption and low emittance properties, are some of the developments of recent years that can be used to improve the thermal and optical performance of ETFE foils and mitigate overheating and glare. Energy savings for cooling demands using a novel ETFE foil with infrared absorbing coatings were calculated to range between 5% and 8% for double and triple layer cushions [38]. Innovative 3D printing techniques applied to the middle layer of triple-layer ETFE foil construction were predicted to achieve even higher energy savings for cooling load of 69–87%, compared to conventional ETFE foil cushions [39]. While these techniques are mainly passive, the technological trend in the development of building envelopes is moving towards adaptive solutions which respond dynamically to the changing weather conditions, effectively control daylighting and reduce energy demands for cooling [40–47]. The most widely reported strategy for the active control of ETFE foil constructions is the switchable multilayer shading mechanism [27,48–51]. A model of a switchable triple-layer ETFE foil cushion with reflective frit print has been constructed at the laboratory of the University of Nottingham, UK (Fig. 1).

ETFE foil cushions function as pneumatic systems that are structurally stabilized by air pressure, which is provided by an air blower unit. The air pressure (in the range 300–600 Pa) keeps the foil tensioned and enables it to withstand external forces, such as wind and snow loads. The ETFE cushions are connected through a pipe network to an air blower, which provides the constant low pressure air flow. The principle of this shading mechanism is based on changing the overall solar transmittance of the cushion unit by controlling the air pressure in the two cavities between the three ETFE foil layers to adjust the position of the moveable middle layer, thus switching between open and closed mode (Fig. 2). While adaptable shading mechanisms for textile membranes rely mainly on mechanically retractable systems, which have been applied in many stadia and amphitheatres, the pneumatically controlled mechanisms for inflated foil construction is relatively new. The concept was first introduced by Robbin in 1996 [52], based on a design study by David Geiger from 1977, and more recently, literature has emerged that offers specific project applications incorporating switchable ETFE cushions [27,53–57].

Despite having been applied and tested in several buildings ("Duales System World Exposition Pavilion" 2000 [58], "Festo Technology Center" 2000 [49], "Kingsdale School" 2004 [48], "Media-TIC Building" 2010 [59]), very little information has been disclosed on the building physics of this adaptable mechanism, and it is still unclear to what degree the dynamic performance of the foil cushion is contributing to the overall energy performance. This deficiency is related to the fact that the relevant material properties data are not widely available in the public domain, resulting in limited implementation in energy performance simulations. The same applies to data collection of long-term performance and post occupancy studies, which have been carried out only to a limited extent, as in the case of the "Media-Tic Building" where user acceptance and comfort was evaluated [59] but a clear link to the envelope performance could not be established. Although extensive research has been carried out, validation of predictive analysis results with specialist software packages and monitoring data remains a challenge for designers and researchers.

The main purpose of this study is to expand the understanding of the environmental behaviour of foil constructions, aiming specifically to investigate the optical performance and the impact on the energy performance of buildings incorporating triple-layer ETFE foil cushions incorporating a dynamic shading mechanism. As part of this comprehensive study a novel method is proposed for the analysis of the switchable ETFE cushions, combining for the first time ray-tracing results with energy simulations. A series of design parameters for ETFE foil cushions, including geometry, curvature and frit prints, were simulated under different solar incidence angles using ray-tracing methods. Ray-tracing has been used previously to examine the optical performance of CFS (Complex Fenestration Systems) [60–62] and offers a practical method to virtually trace solar beams through geometrically complex components such as pneumatic foil constructions. The results of the optical simulations showed a distinctive optical profile for the switching modes of the cushion and provided insights into the angle dependent behaviour of the different designs. This allowed the optical data to be integrated into a building energy model for a realistic atrium building in order to compare frit print design variations of the switchable ETFE foil cushion with common glazing systems. The building simulation software, EnergyPlus [63], was used to predict the energy and lighting performance of the building and moreover explore the performance of the switchable ETFE cushion under different climate conditions. Outcomes of this study deliver advice on the design parameters of switchable ETFE cushions and aim to support decision making of architects and engineers for the system integration in future buildings.

2. ETFE cushion: geometry and frit pattern design

As a first step in this study of optical ray-tracing analysis, the cushion geometry of an inflated triple-layer cushion was generated. This was carried out using a combination of 3D modelling software, a series of plug-ins and in-house developed software components. The form-finding procedure is based on the Updated Reference Strategy (URS). This method generates the equilibrium shape and main stresses for tensioned membrane structures [64]. The specific method of modelling pneumatic multilayer cushions has been described extensively