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Thermal Environment of an atrium enclosed by an ethylene-tetra-fluoro-ethylene (ETFE) foil cushion roof

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Abstract

This paper presents on site monitoring results of a study of the thermal environment of an atrium enclosed by an ethylene-tetra-fluoro-ethylene (ETFE) foil cushion roof, including distribution of air temperatures, mean radiant temperatures, foil surface temperatures and incident solar radiation. The aim was to evaluate environmental aspects of an ETFE foil cushion roof system.

ETFE-foil has been most commonly employed to enclose transitional spaces, for example atria and external circulation areas, but, increasingly, it is being used as a secondary or primary façade for more intensively occupied architectural spaces where thermal comfort needs to be more precisely controlled. Although the structural behaviour of ETFE-foil has been examined in some detail, to date, environmental aspects in terms of thermal performance have not been studied or analysed with rigor and depth. Increasing frequency of building integration of ETFE-foil cushion systems in more complex and permanent enclosures has made it necessary to examine their effects on the internal thermal environment so that the comfort conditions can be better understood and the undesirable thermal issues can be identified and addressed.

Field measurements of the winter thermal environment within an approximately 625m^2 atrium covered with a two-layer ETFE cushion roof are used to clarify the characteristics of an actual ETFE cushion envelope. Continuous monitoring was conducted from December 2013 to April 2014 covering overcast and clear days and nights. Measurements of indoor thermal environmental parameters were conducted at different levels in the atrium and the recorded data represent the internal conditions with and without operation of the HVAC system. The effects of solar transmission, outdoor air temperatures, and surface temperatures of the ETFE cushion on internal air temperatures at different levels of the atrium are discussed. This study reveals the thermal conditions of the chosen atrium space and provides monitored data which will enhance the holistic understanding of the thermal environment created by the ethylene-tetra-fluoro-ethylene (ETFE) foil cushion roof structure.

Keywords: ETFE foil cushion, atrium, temperature, façade, light-weight roofs, environmental performance, thermal performance, solar transmission, ETFE roof, lightweight building envelope.

1. Introduction

Ethylene-tetra-fluoro-ethylene (ETFE) is a synthetic fluoropolymer that has been known since the 1940s. It is generally recognized that the first large-scale use of extruded ETFE foil in permanently inflated cushions – where air volumes between foil layers typically less than 250μm thick act as a thermal barrier between the interior and exterior - was for the roof of the Mangrove Hall at Burgers' Zoo, in Arnhem, The Netherlands, constructed in 1982 (LeCuyer [5]). Since then there have been developments in the material, technology and installation systems. These have increased ETFE foil's use in architectural applications (Chilton, [1]) such that the material is now widely used as a lightweight building envelope where high translucency, low structural weight and complex shape is essential.

Research has shown that the architectural application of ETFE foil has expanded more rapidly in temperate humid climatic conditions such as Germany and the UK (Gómez-González, et al.[4]). This has led to the use of ETFE foil cushions as the primary building envelope of impressive large-scale projects such as the Eden Project in Cornwall, UK (completed in 2000), the Allianz Arena in Munich (built in 2005), the National Stadium 'Bird's Nest' and National Aquatics Centre 'Watercube', in Beijing (built for the 2008 Olympics) and the Dolce Vita

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Tejo shopping mall, Amadora, Portugal (2009), (Chilton, [1]). These projects have moved ETFE foil and its construction tectonic into the public's architectural attention (Schiemann and Moritz [8]).

In recent times, due to the increasing awareness of the effect of energy consumption/CO_2 production on climate change, the impact of building materials on the environment has become a major consideration for designers. As a consequence, ETFE foil envelopes have become a subject of critical consideration, as they are increasingly installed throughout different continents. As substantial energy saving is possible by exploiting the high transparency of ETFE foil, it is necessary to examine the appropriateness of its application in terms of thermal performance, which is, as yet, relatively unexplored.

2. Background

Because of their high light transmission and transparency, ETFE-foil cushions are now widely used as an alternative to glass as a cladding for complex structures. The purpose of the advancement of ETFE foil in the building industry was to reduce material cost whilst at the same time gaining benefit from improved comfort, aesthetics, and safety. Integration of this material reduces embodied energy by reducing the quantity of materials used and the size and complexity of supporting structures in comparison to glass (Chilton,et al [2],[3]). Moreover as a transparent foil material, ETFE foil allows flexibility in building geometry, reduces fragility and weight of the building components, whilst providing sufficient access to light and heat (Robinson-Gayle, et al.[6]).

An atrium consists of a high interior space in a building. It is normally covered by a large transparent roof and surrounded by walls of several storeys, providing a central core circulation area and transitional zone between interior and exterior with a feeling of space and light, encouraging users to prolong their stay (Saxon [7]). Environmental conditions in the atrium depend on a complex interaction between outdoor weather condition and building envelope directly in contact with the outdoor environment. The transparent building envelope incorporated into an atrium allows deeper penetration of high levels of natural light and strong solar radiation. This can create either a pleasant environment or, if designed incorrectly, adverse factors such as glare and poor thermal comfort.

A transparent polymer membrane e.g. ETFE-foil cushion envelope can be considered as a passive environmental filter for an atrium, oin order to moderate the external environment. At the same time solar radiation penetration through the ETFE cushion envelope can potentially adversely impact and impair the atrium's thermal environment. Accurate prediction of this impact requires a detailed knowledge and understanding of the ETFE-foil envelope's thermal behaviour . In order to better understand this continuous field monitoring of a double-layer ETFE foil cushion covered 625m^2 atrium has been carried out since December 2013. . Results obtained from two different sky conditions and its impact on the internal thermal environment during the months of December 2013 and April 2014 are presented here.

The study method was *in situ* measurement and monitoring of indoor and outdoor thermal environmental parameters, including internal and external incident solar radiation, external and internal surface temperature of an ETFE foil cushion, outdoor ambient temperature, and temperatures at different levels in the atrium. The recorded data represents the thermal behaviour of an ETFE foil cushion under different sky conditions and the indoor thermal environment of the atrium with and without operation of the HVAC system. A primary aim of the study was to evaluate the thermal behaviour of an ETFE foil cushion by identifying its response to external weather conditions e.g. outdoor ambient temperature and solar radiation, and to seek the response of the atrium's indoor thermal environment to the changes in physical behaviour of the ETFE cushion envelope.

3. Field measurement

Local weather data was collected from an on-site weather station database on a regular basis. Measurements to observe changes in incident solar radiation, foil surface and air temperature distribution under the test ETFE foil cushion roof were conducted continuously from December 2013 to April 2014.

3.1 Description of building and roof system

The three-storey school building, located near the centre of Nottingham, was built in 1860-1960. It has a central courtyard which was roofed over during 2009 to form an enclosed atrium, also three storeys high. This contains a dining hall and cafeteria on the ground floor and first floor, respectively, and a study space for students on the second floor (Figure 1). The atrium roof consists of 25, two–layer, ETFE cushions, complete with aluminum

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framing, inflation and air management equipment with associated air handling pipe work and connections. In turn these are supported by steel trusses and columns.

Figure 1: Atrium of Nottingham High School (Photo: Sabrina Afrin)

3.2 Environmental control system

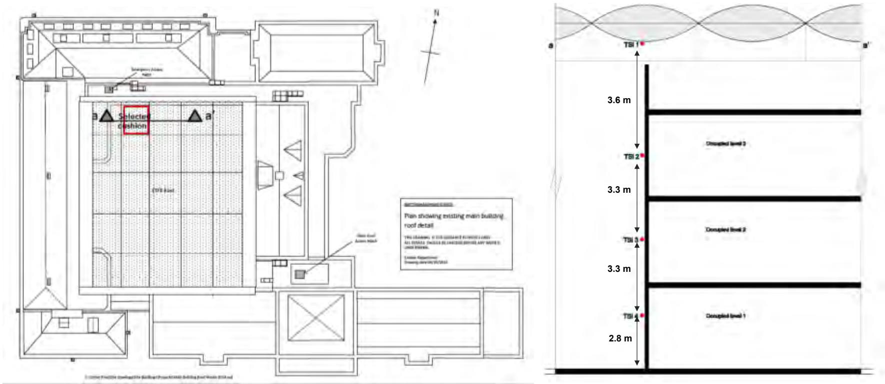
The building space heating system consists of fan coil units, fan convectors, under floor heating systems and mechanical ventilation, controlled by a Building Management System (BMS). It operates on a global time zone set from 08.00 to 18.00, Monday-Friday, and is turned off at weekends. Natural ventilation operates automatically through windows at high level (on the west side only) in conjunction with dampers located above north and south entrance doors at the ground floor.

3.3 Monitoring of weather data, incident insolation and temperature

Weather data was collected from the weather station located on the roof of the school. Data on outdoor ambient temperature and humidity was collected at 5 minute intervals. However, for analysis, data at 30 minute intervals were selected. External and internal incident solar radiation was measured by two pyranometers, placed adjacent to the cushion one internally and the other externally.

Table 1: Description of measurement sensors

Measurement type	Sensor type
Air Temperature and foil surface temperature	ϕ0.1 mm K-type thermocouple connected to DT 85 data logger
Total horizontal solar radiation	Kipp & Zonen CMP3 Pyranometer (sensitive wave band: 0.3-2.8μm)



(a) (b)

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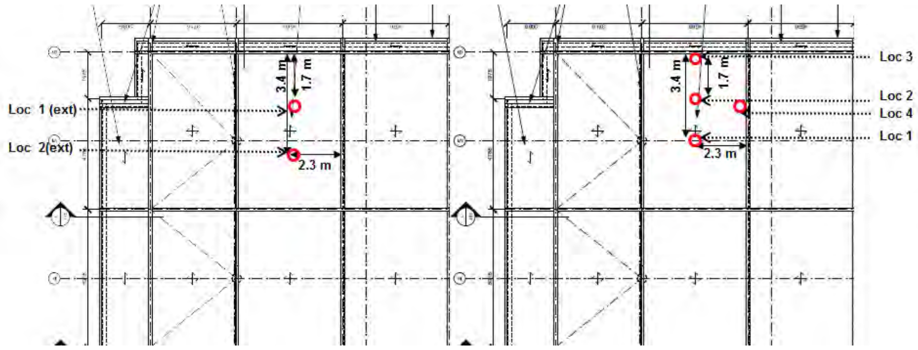
Figure 2: (a) Plan (nts) showing ETFE cushion roof and location of the monitored cushion, outlined in red (Drawing courtesy of Maber Architects, Nottingham), (b) Section showing vertical location of temperature sensors (Drawing: Sabrina Afrin)

Diurnal variations of air temperatures at different levels in the atrium and cushion surface temperatures were continuously measured with screened thermocouples. Measurement points were as illustrated in Figure 2. The data was collected at one minute intervals from December 2013 to April 2014. However, data presented here in graphical format is at 30 minute intervals. Descriptions of temperature and radiation sensors are stated in Table 1.

Table 2: Location of temperature sensors

Temperature sensor identification	**Location**
TSi 1	Adjacent to ETFE cushion 1 surface
TSi 2	Second floor (occupied level)
TSi 3	First floor (occupied level)
TSi 4	Ground floor (occupied level)

In spite of the 'non-stick' characteristics of ETFE foil, during the monitoring period it was possible to attach temperature sensors to the ETFE cushion surface. Locations of temperature sensors attached to the cushion surface are as described in Table 3.



(a) (b)

Figure 3: Plan (nts) showing ETFE cushion selected for monitoring and location of temperature sensors outlined in red (Drawing courtesy of Architen Landrell, Chepstow) , (a) location of temperature sensors attached on external surface (b) location of temperature sensors attached on internal surface

4. Results and discussion

Weather conditions during the monitored period varied. It was noticed that variation in sky condition affected the internal thermal environment of the atrium. Two different patterns in the thermal behavior of the ETFE cushion envelope were identified based on the clearness of the sky. Inspection of the weather data and external incident solar radiation during the month of April showed that two consecutive days were sunny and overcast, respectively. Maximum and minimum levels of incident solar radiation were found on those two days. In a similar way, representative sunny and overcast days were also identified for the month of December.

4.1. Thermal behavior of atrium enclosed with ETFE foil cushion

Figure 3 and Figure 4 present indoor air temperatures on different atrium levels, outdoor air temperature, external and internal incident solar radiation, external and internal surface temperature of the foil cushion for

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warm and cold sunny and overcast days in April 2014 and December 2013 respectively. During selected days in April result demonstrated here include impact of HVAC system also while selected days in December were weekend and holiday period so HVAC system was not in operation on that time. Indoor air temperature here represents air temperature at a particular time of day for different measuring points along the same vertical line at each floor.

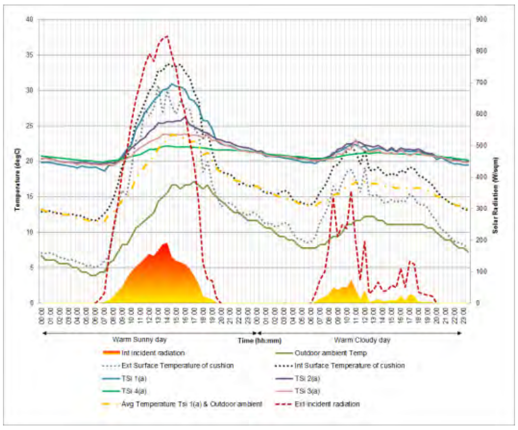

Figure 3: Typical thermal behaviour of the atrium during two consecutive days (one warm sunny and one cloudy) in April 2014

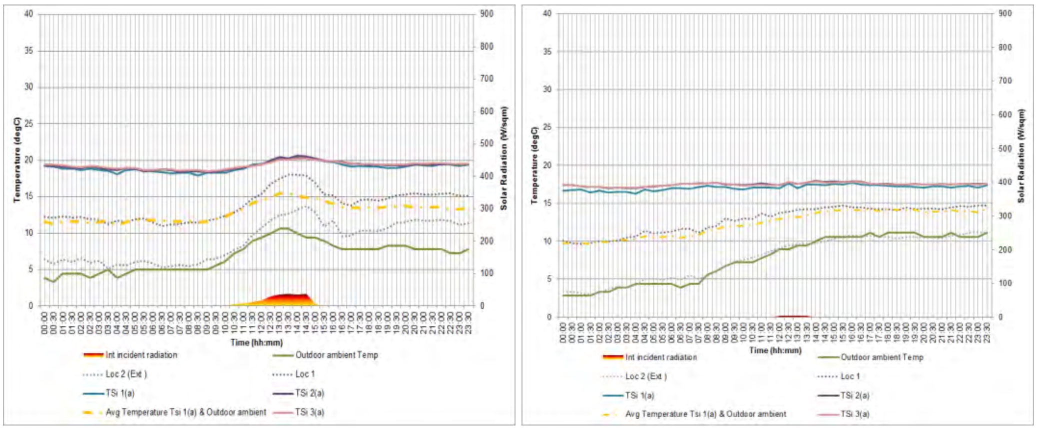

Figure 4: Typical thermal behaviour of the atrium during cold sunny (left) and cold cloudy (right) days in December 2013

From Figure 3 it can be observed that the internal thermal environment (shown by TSi 4) on the ground floor was not greatly affected by outdoor weather conditions. This was due to the HVAC system, shading from the floors above and the thermal inertia of the adjacent stone masonry walls and atrium floor. The internal air temperature on the ground floor during both the warm clear sunny day and overcast day agreed well with the indoor design temperature, remaining reasonably stable between about 20°C and 22°C over the whole period. However, during the clear night the air temperature at ground floor was approximately 1°C warmer than air immediately below the cushion surface. Correspondingly, air temperature at the first floor (shown by TSi 3) was slightly higher than that at the ground floor and slightly more affected by outdoor weather conditions. During warm sunny day the temperature difference between ground and first floors varied by approximately 1 to 2°C between 12.00 and 20.00, with the maximum difference observed during late afternoon and evening. The highest temperature recorded at first floor over the two days was 24°C. During the sunny April day the direct and diffuse radiation could penetrate more deeply to lower atrium levels resulting in raised air and mean radiant temperatures. On the second floor air temperatures (shown by TSi 2) were higher than ground and first floor. During the afternoon of the sunny day second floor air temperatures rose to 25°C then increased to a maximum of 26.3°C. It is considered that the main reason for this is the proximity of the translucent ETFE cushion roof to

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this atrium level which increases the sky view factor and radiant heat effects from the roof. Besides, a significant temperature rise was observed in air temperature adjacent to the inner surface of the foil cushion, 6°C higher than the second floor air temperature. The amount of incident solar radiation affects thermal environment on the second and third floors significantly, creating strong vertical positive stratification during day time, whilst absence of solar radiation and long wave radiation to a clear cold sky from the upper level may cause negative stratification at night. This positive and negative stratification was also observed during the overcast day but to a lesser degree. During the warm sunny and overcast days the maximum temperature difference between TSi 1 and TSi 4 was 9°C and 1.4°C respectively, whereas between TSi 2 and TSi 4 it was 4.3 and 1.6°C correspondingly.

From Figure 4 it can be observed that the variation of temperature at different atrium floors during cold sunny and overcast days in December 2013 was not as significant as on the warm sunny day in April 2014. In December the maximum measured internal incident solar radiation was 19.4% of that measured during April. Maximum temperatures observed at TSi 1, TSi 2 and TSi 3 varied between 20°C and 20.6°C in the afternoon on the cold sunny day, whereas it was between 17.7°C and 18°C for the specified locations during cold cloudy afternoon. It was mentioned previously that on selected cold sunny and overcast days no HVAC system was in operation. Minimum temperature observed was 18 °C and 17 °C during cold sunny and overcast day. Because of low solar gains into the enclosures vertical temperature stratification was very weak during winter months. During day and night for both of the days an almost uniform temperature was observed within the space.

4.2. Thermal behavior of ETFE foil cushion

Figures 5 and Figure 6 illustrate external and internal surface temperature at different locations on the ETFE cushion, external and internal incident solar radiation, air temperature TSi 1 just below the cushion and outdoor ambient temperature. Figure 5 shows consecutive warm sunny and cooler cloudy days in April 2014, while Figure 6 shows cold sunny and cold cloudy days in December 2013.

From Figure 5 it can be observed that for both monitored periods in the absence of solar radiation the internal surface temperature of the ETFE foil was similar to that of the average between indoor and outdoor ambient temperature. On the warm sunny afternoon the maximum internal foil surface temperature was 36.5°C, while the adjacent air temperature TSi 1 was 31°C. At night external surface temperatures stayed close to external air temperature during both warm and cold sunny and overcast days. But variation was observed during the warm sunny, warm overcast and cold sunny days. As soon as the sun rose, external foil surface temperature rose above external ambient temperature. A sharp increase in surface temperature was observed just after sunrise on the warm sunny day. During that period the external surface temperature reached close to the internal surface temperature. Maximum and minimum temperature difference observed between the internal and external surfaces of the ETFE cushion were 7.5°C and 0.58°C on the clear warm sunny day, whereas during the cold sunny day this difference was 6.4°C and 3.5°C.

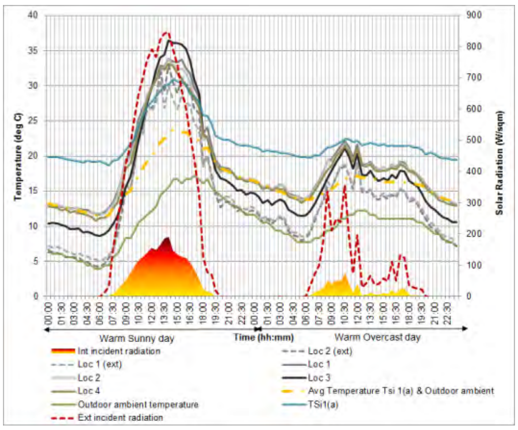

Figure 5: Typical thermal behaviour of the ETFE cushion during consecutive warm sunny and cloudy days in April 2014.

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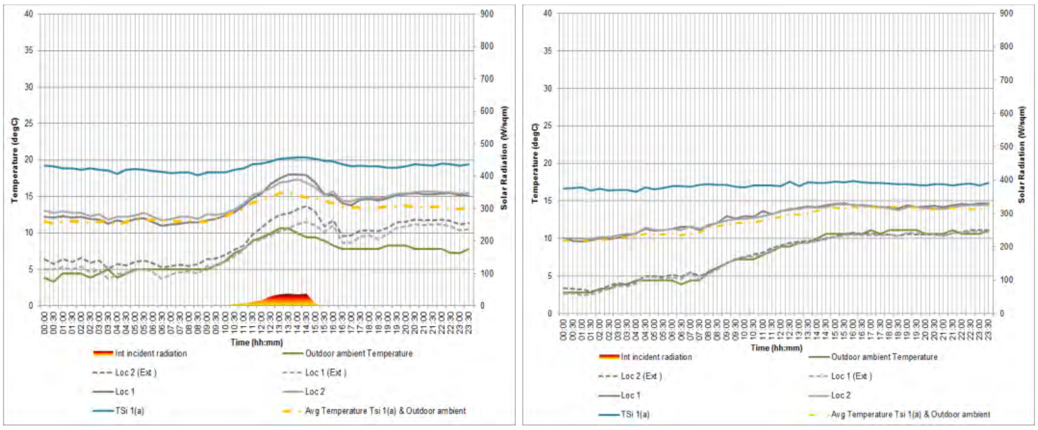

Figure 6: Typical thermal behavior of the ETFE cushion during cold sunny and cold cloudy days in December 2013.

Results of the monitoring showed that an increase (or decrease) in solar radiation directly impacts foil surface temperature, both external and internal. This was observed on both warm and cold sunny, and warm cloudy days. In the presence of cloud internal surface temperatures of the ETFE cushion remained close to the average between indoor and outdoor air temperature. This was also apparent when there was no insolation. During the warm and cold cloudy days, the limited amount of diffuse radiation filtering through the cloud and high mean radiant temperature of sky resulted in radiative heat exchange as well as convective heat transfer at the surface of the cushion. During the warm sunny day radiative heat exchange effects dominated those of convective heat transfer. As a result a higher difference was observed between foil surface temperatures and the average of indoor and outdoor ambient temperature. Moreover, air in between the cushion layers creates a thermal barrier between the two 200µm ETFE foil layers and the external and internal air. For that reason, although the external surface temperature stays close to the outdoor air temperature in the absence of solar radiation, the internal surface temperature is always higher than that of the external surface temperature.

On the warm sunny day at mid-day the internal surface temperature was influenced by convective heat transfer at the surfaces of the cushion, also radiation from the sky and internal surfaces. Warm air from the lower occupied levels rises to the upper level and this impacts temperature TSi 2. As there was no opening for the warm air to escape through at high level it also influence the surface temperature of the cushion as a process of convective heat transfer. Therefore the temperature of internal surfaces rose above the air temperature of TSi 1. Warm air rising from the lower levels is also heated by internal incident radiation entering through the transparent ETFE cushion roof impacting the temperature of TSi 1 and TSi 2.

The roof demonstrated more extreme thermal behavior under clear sky conditions where both direct solar and long-wave infrared radiation appeared to govern the fluctuation of the ETFE surface temperatures. It was noticed that before sunset external and internal surface temperature respectively drop by 8°C and 6°C within 1 hour due to the long wave radiation losses to the exposed sky dome. Here solar radiation reaching the surface was insufficient to counterbalance this long wave radiation loss. The minimum difference between internal surface and outdoor air temperature observed at this time was 3.24°C. After this hour a gradual decrease of surface temperature was observed until just before sunrise. This also had an impact on the temperature of TSi 1.

Because of ETFE foil's higher transparency to long wave radiation, when compared to glass, radiation losses from the foil surfaces caused a drop in surface temperature. This in turn had an impact on the air temperature at TSi 1. It also resulted in negative stratification at night. The internal surface temperature was lower than the TSi 4 temperatures, the opposite scenario to that observed at mid-day with bright sunshine. After sunset the external foil surface temperature stays close to the external air temperature but the internal foil surface temperature is approximately equal to the average of indoor and outdoor air temperature, due to long wave radiation exchange to the clear night sky and convective heat transfer effects. A gradual decrease in foil surface temperature was observed until about 1 hour before sunrise. During bright sunny days both foil surface temperatures are greater than the air temperature immediately below the cushion TSi 1, from morning till late afternoon.

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5. Conclusion

This study of the thermal behavior of an atrium space enclosed by an ETFE cushion roof has shown that, under warm sunny conditions encountered during April 2014, buoyancy forces created by solar gains induced warm air to rise in the enclosure leading to significant thermal stratification and the accumulation of a reservoir of warm air directly under the ETFE roof. The combination of direct solar radiation from the high altitude afternoon sun and high temperature stratified air could potentially create thermal discomfort at the higher levels of the atrium especially in the area immediately under the ETFE cushion roof. The fact that no evidence of rapid destratification, of the sort that would have resulted in the mixing of air in this reservoir of warm air with air in the lower occupied level, was observed suggests that potentially high cushion surface temperatures may have stabilized this warm layer in the upper part of the enclosure. Although there is a HVAC system installed and automatic window venting neither of these systems was sufficient to control heat gain on the upper level. This suggests that without an appropriate ventilation system this type of innovative envelope may cause overheating. When the HVAC system was not operating, at weekends, on the cold sunny and the cloudy day the air temperature was reasonably comfortable and remained in a stable condition on the occupied floors.

From the result of this study it is clear that convection heat transfer occurs during the absence of solar radiation on overcast days. As a result, the surface temperature of the external cushion foil layer was fairly close to the outdoor air temperature whereas the internal foil surface temperature was maintained close to the average between the adjacent outdoor and indoor air temperatures. Just after sunrise radiative heat transfer governs and for that reason the surface temperature rises significantly under the influence of direct and diffuse radiation. However, during the overcast day this was only influenced by diffuse radiation in the absence of direct radiation. A sharp rise in surface temperature as well as surrounding air temperature at sunrise confirmed that radiative heat transfer governs over convective heat transfer under clear conditions.

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