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Evaluation and Comparison of Thermal Environment of Atria Enclosed with ETFE Foil Cushion Envelope

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Abstract

This paper presents results of on-site monitoring of foil surface temperatures and the thermal environment within two different atria covered with different compositions of ETFE foil cushion roof (one two-layer, the other three-layer) and differing ventilation regimes. Results of the study show strong vertical stratification in both atria. Foil surface temperatures respond rapidly to high solar radiation with the internal layer being hotter than both the external layer and the adjacent internal air. At night the surface temperature of external foil follows the ambient external temperature closely whilst the internal layer temperature follows approximately the mean of adjacent internal temperature in the atria and external temperature.

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*Keywords:*ETFE cushion envelope, building performance, building continuous monitoring, thermal environment, solar radiation transmission

1. Introduction

Ethylene-tetra-fluoro-ethylene (ETFE) is a synthetic fluoropolymer. In the form of ETFE-foil (typically 100μm to 300μm in thickness) it is applied in building envelopes in a single layer or, more commonly, as inflatable cushions composed of multiple layers. As a highly translucent material ETFE foil allows flexibility in building geometry, with reduced fragility and weight of the building components (typically less than 1.0kg/m^2 for three-layer cushions) while providing adequate access to light and heat [3,4]. Its integration reduces embodied energy by reducing supporting structures in comparison to glass [1,2,3]. The ETFE-foil cushion envelope can be considered as a passive environmental filter to moderate the external environment but at the same time high transmission of solar radiation

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can result in overheating of enclosed spaces. Double curvature of the cushions and their high solar transmittance over a wide spectrum makes prediction of the internal environment more difficult and suggests that existing standards for conventional materials cannot be directly applied for ETFE-foil cushions [5]. In order to understand the thermal behaviour of ETFE foil cushions and the environment they enclose, continuous field monitoring was carried out in two different atria with different configurations of ETFE foil cushions constructed with different number and thickness of foil layers. Monitoring started in November 2013 and is ongoing. A discussion of the earlier results can be found in [6]. Mainly thermal data collected in the extreme summer situation is highlighted and analysed here.

2. Description of building and environmental control system

2.1. Case Study A

The three-storey school building, located in Nottingham, was originally built in 1860. It has a central courtyard which was renovated during 2009 to form an enclosed atrium. The three-storey high atrium contains a dining hall and cafeteria at ground floor and first floor respectively, and a study space for students on the second floor. The atrium roof consists of two–layer ETFE cushions with fritted top layer and clear bottom layer both of 200µm covered with a rain noise suppression mesh. This roof, see Figure 1(i) and (ii), is complete with aluminium framing, inflation and air management equipment with associated air handling pipe work and connections. In turn these are supported by steel trusses and columns so that the atrium roof structure does not bear on the existing school buildings. The atrium 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 (located on the west side only) in conjunction with dampers located above north and south entrance doors at the ground floor.

2.2. Case Study B

The Engineering & Science Learning Centre at the University of Nottingham is located at the University Park Campus. This three-storey building contains support centre, graduate centre, learning and teaching space and a central atrium used for multipurpose activities. Varying capacity rooms are arranged off the atrium on all three floors. The atrium roof, see Figure 1(iii) and (iv) consists of three layer ETFE cushions with fritted top layer (200µm) transparent middle (150µm) and bottom layer (150µ m), which are edge clamped to extruded aluminium framing connected to the primary steel truss structure. The primary heating system in the atrium consists of ground source heat pump, district heating, under floor heating system with BMS controlled heating/cooling. Glazed motorised louvres are provided at both low and high level of the atrium to maintain the temperature and CO_2 levels at comfortable levels. This ventilation system operates if the temperature exceeds 21°C during weekdays or 25°C at the weekend.

3. The monitoring setup

Site weather data was collected from weather stations located on the roofs of the school and the Engineering & Science Learning Centre (ESLC) respectively. The coupled indoor-outdoor continuous monitoring was performed through a set of sensors which were operating continuously since November 2013 for Case Study A and August 2014 for Case Study B. The equipment used for monitoring is listed in Table 1. Solar radiation and temperature sensors were connected to dataTaker DT85 (Case Study A) and dataTaker DT80 (Case Study B) data loggers to measure and record data at 1 minute intervals. However, for analysis, data recorded at 5 minute intervals were extracted. Diurnal variations of cushion surface temperature and air temperature at different levels in both atria were continuously measured with screened thermocouples. 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. Surface temperature was also verified using thermal imaging.

Table 1.Description of measurement sensors.

Measurement type	Sensor type
Air temperature and foil surface temperature	$0.1 mm K-type thermocouple connected to dataTaker DT 85 or dataTaker DT 80 data logger
Total horizontal solar radiation (internal & external)	Kipp & Zonen CMP3 Pyranometer (spectral range: 0.3-2.8µm)
Foil surface temperature	FLIR T400

Table 2: Temperature and solar radiation sensor identification

Case Study A	Case Study B	Location
TSi 1_A	TSi 1_B	Ground floor (occupied level)
TSi 2_A	TSi 2_B	First floor (occupied level)
TSi 3_A	TSi 3_B	Second floor (occupied level)
TSi 4_A	TSi 4_B	Internal adjacent to ETFE cushion
TsExt_A	-	External foil surface temperature
TsInt_A	Ts Int_B	Internal foil surface temperature
OAT_A	OAT_B	External ambient temperature
ExIR_A	ExIR_B	Incident solar radiation
InIR_A	InIR_B	Transmitted solar radiation

(i) (ii) (iii) (iv)

Figure 1: (i) and (ii) Case Study A, (iii) and (iv) Case Study B

4. Result and discussion

This section presents the analysis of the continuous monitoring by the assessment of indoor thermal behaviour for both atria in August 2014, as representative of typical summer conditions. Comparative analysis of the thermal behaviour of the atria was made through the analysis of indoor air temperature and incident solar radiation. Thermal behaviour of the ETFE-foil cushion envelope is evaluated through the analysis of its surface temperature.

4.1. Vertical distribution of internal air temperature

Internal and external air temperatures and incident and transmitted total solar radiation are reported in Figure 2. Indoor temperatures are at shielded measuring points along the same vertical line at each floor. To quantify the variability of the measured thermal parameters hourly and daily profiles are assessed. The second week, 4th to 10th August 2014, was the hottest of the month and in both atria the highest air temperature was observed on 7th August 2014. Table 3 presents the maximum, minimum, average and standard deviation (SD) for air temperatures recorded in both atria on that date. From Table 3, it can be observed that the thermal environment of Case Study B was generally hotter than that of Case Study A at all levels.

Table 3: Maximum, minimum, average and standard deviation (SD) air temperatures recorded in atria, 7th August 2014, (Notation as Table 2)

	Case Study A					Case Study B				
Location	OAT_A	TSi 1_A	TSi 2_A	TSi 3_A	TSi 4_A	OAT_B	TSi 1_B	TSi 2_B	TSi 3_B	TSi 4_B
Maximum	23.8	23.9	24.6	27.7	34.9	27.2	25.96	27.8	28	39.4
Minimum	14.9	20.5	21.2	21.5	21	14.3	21.4	22.6	22.4	19.8
Average	19.4	21.9	22.9	23.8	26	20.32	23.4	24.2	24.4	26.2
SD	2.9	0.9	1.13	1.83	4.52	4.14	1.01	1.4	1.63	5.62

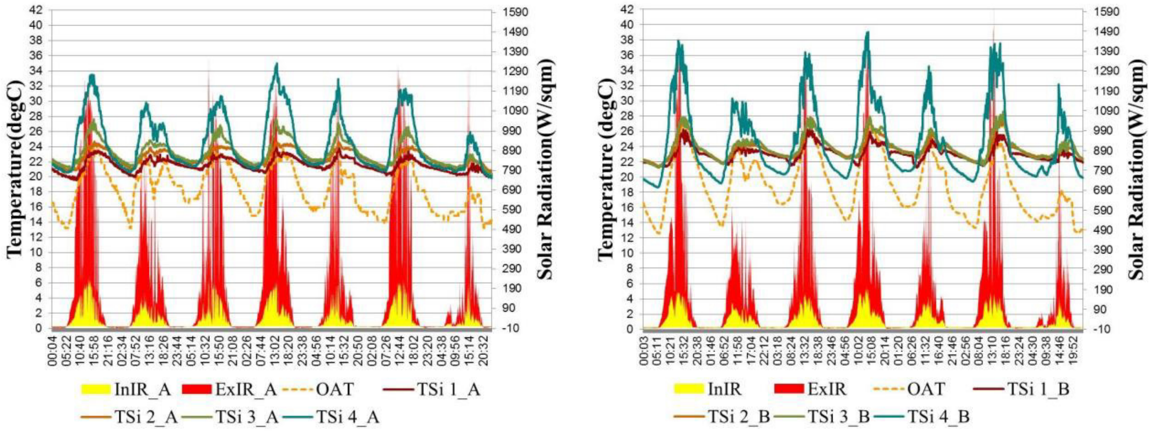

Figure 2: Typical recorded thermal/solar radiation data for Case Study A (left) and Case Study B (right) from 4th to 10th August 2014 (Notation as Table 2)

Figure 2 shows that for Case Study A the ground floor temperature is generally the lowest and that it is relatively unaffected by external conditions (20.8 °C ~23.9°C compared to 14.9~23.8°C for the external ambient temperature). For Case Study B, similar behaviour was observed during the day but with a greater temperature range (22.6°C ~26°C compared to 14.6~27°C for the external ambient temperature). At night the lowest atrium air temperatures were recorded in the zone immediately below the cushions. On 7th August ground floor temperature around mid-day was lower than the external ambient temperature for both atria (21°C~23°C for Case Study A and 23°C~25°C for Case Study B). In both atria strong positive stratification was observed during day time (maximum of 11.2°C difference between TSi 1_A and TSi 4_A and 15°C difference between TSi 1_B and TSi 4_B) whereas negative stratification occurred at night, most significantly in Case Study B (with 2.7°C difference between TSi 1_B and TSi 4_B). Positive and negative air temperature stratification was found to be more significant in Case Study B. To determine the relationship between different environmental parameters the Pearson correlation coefficient formula was used. Results showed that the internal incident radiation had a strong positive relationship with air temperature adjacent to the cushion (0.8). Strong correlation was also found between air temperatures TSi 4_A, TSi 3_A, TSi 2_A and TSi 1_A, which were around 0.88~0.98.

4.2. ETFE foil cushion surface temperatures

Both internal and external surface temperatures of the roof were evaluated to investigate the dynamic thermal responsiveness of ETFE foil cushions under variation of external weather conditions. Figure 3 (top left) reports the external (TsExt_A) and internal (TsInt 4_A) foil surface temperature profiles, ambient external temperature (OAT), internal air temperature adjacent to the underside of the cushion (TSi 4_A), incident and transmitted total solar radiation for Case Study A during the second week of August 2014. Figure 3 (top right) shows external and internal foil temperatures relative to external ambient temperature (TD_Ts Ext_A_OAT and TD_Ts Int_A_OAT respectively), internal foil temperature relative to external foil temperature (TD_Ts Int_A_Ts Ext_A) and internal foil temperature relative to the adjacent air temperature (TD_Ts Int_A_TSi 4_A). Figure 3 (lower middle) shows the internal surface temperatures of Case Study A and Case Study B from midday to 17.00. During the night the external foil surface temperature remains below external ambient temperature (due to radiation to the cold sky) while the internal foil surface stayed close to external ambient temperature due to the impact of the internal air temperature adjacent to the cushion (TSi 4_A). During that time the minimum temperature of external and internal foil surfaces was observed to be 12.5°C and 16.5°C respectively, when the external ambient temperature was 15°C. Maximum temperature difference between external and internal foil surface was found to be 5.3°C on 6th August around midday whilst the maximum recorded external surface temperature was 45.2°C on 8th August when the internal surface temperature was 41.5°C and the maximum internal surface temperature was 42.4°C on 7th August when external surface temperature was 44°C. Internal surface temperature of the cushion in Case Study A varies more rapidly than Case Study B. At 13.00 the cushion surface temperature of Case Study A is 9°C higher than that of Case Study B, although just over an hour later the situation was reversed with B hotter than A by 2.5 °C. This variation may be due to the impact of number of foil layers and/or different insolation levels at the two sites.

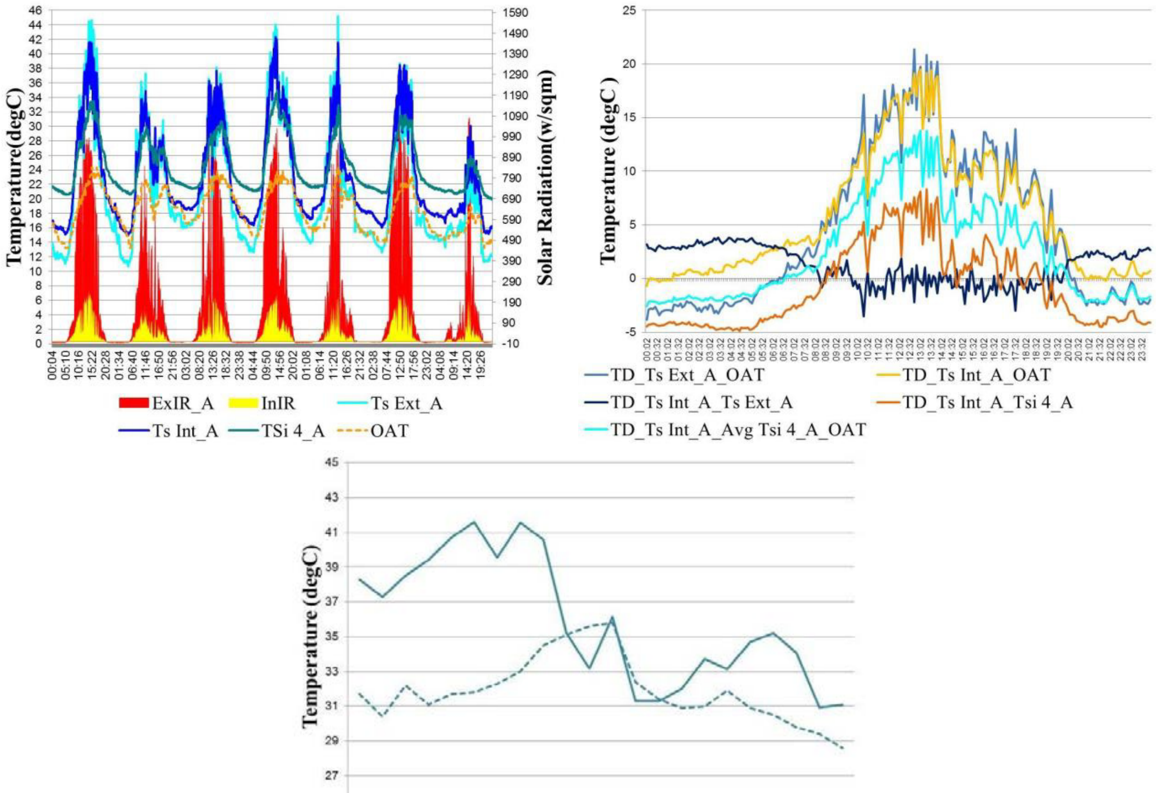

Figure 3: Surface temperature variation week 2 August (top left), surface temperatures with respect to external ambient (OAT) and TSi 4_A on 7th August 2014 (top right), internal surface temperature variation of Case Study A and Case Study B (lower middle)

An increase (or decrease) in incident solar radiation directly impacts on internal and external foil surface temperature, with rapid change in temperature. This was evident on 8th August when a sudden increase of incident radiation from 310W/m^2 to 947W/m^2 caused an increase of external surface temperature from 31.3°C to 45.2 °C within 20 minutes. During clear nights the external ETFE foil surface temperature drops below external ambient. This effect is also evident at the internal surface, which is up to 5°C cooler than the adjacent atrium air. As the plot of (TD_Ts Int_A_Ts Ext_A) in Figure 3 (lower middle) shows, generally, the surface temperature of the internal foil layer was found to be higher than that of the external surface. However, during periods of sudden intense solar radiation the opposite scenario was observed. The Pearson correlation formula was used to determine the interrelationship between ETFE foil surface temperatures and measured environmental parameters. This found a strong correlation between external and internal surface temperature and solar radiation (0.87 and 0.89 respectively) whereas internal incident radiation had a strong positive relationship with internal surface temperature (0.9).

5. Conclusions

Relatively stable thermal conditions were preserved at ground floor level in both atria when compared to the other two occupied levels. This was more noticeable in Case Study A where masonry walls surrounding the atrium provided higher thermal inertia. During the day, there was pronounced thermal stratification. At night stratification was less pronounced and at times negative in upper levels of the atrium.

Solar radiation intensity was found to impact rapidly on both external and internal ETFE-foil surface temperature, with maximums in the range 40~45°C. Temperature difference between foil layers was found to generally be within ± 2°C, see Figure 3 (lower middle). With similar levels of insolation the air temperature adjacent to the inner foil layer was significantly higher in Case Study B, reflecting the higher level of thermal insulation provided by the 3-layer cushion. At times the high surface temperature over the large roof area may adversely affect user thermal comfort. Maximum temperatures of 27°C~28°C were recorded at occupied level 3.

At night, longwave radiation exchange to the clear sky cooled the outer foil to around 3°C below external ambient temperature, with internal foil typically 3~4°C warmer. Nocturnal air temperature immediately below the cushion was found to be typically 9°C warmer than the external air.

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