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MEASUREMENT AND SIMULATION OF SUMMER THERMAL ENVIRONMENT OF AN ATRIUM ENCLOSED WITH ETFE FOIL CUSHION ROOF

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Summary: *This paper presents a study to investigate the summer thermal environment of an atrium enclosed with an ETFE cushion envelope using field measurement and simulation. Continuous monitoring was conducted from May 2014 to July 2014 covering sunny and overcast days and nights. Results of the study also examine general thermal performance of ETFE foil cushion envelopes. Measurements of the indoor thermal environmental parameters were conducted at different vertical levels and horizontal positions in the atrium and the recorded data represent the internal conditions with and without operation of the HVAC system, with variable occupancy. The effects of solar transmission, external ambient air temperatures, humidity and surface temperatures of the ETFE cushion on internal air temperatures, mean radiant temperatures and humidity at different levels of the atria are discussed. Impact of solar transmission, air temperature and humidity on user thermal comfort is also assessed. Results obtained from on-site monitoring are compared with those from a predictive model using the dynamic environmental simulation tool TAS.*

Result of the monitoring showed the following:

- *Relatively stable thermal conditions at ground floor level*
- *Daytime accumulation of a reservoir of warm air immediately below the ETFE cushion with pronounced thermal stratification.*
- *Negative stratification at upper levels of the atrium at night*
- *Rapid change of external and internal ETFE-foil surface temperature according to solar insolation levels*
- *High insolation and high ETFE surface temperature may adversely affect user thermal comfort in particular at higher levels of the atrium.*

1 INTRODUCTION

Ethylene-tetra-fluoro-ethylene (ETFE) is a synthetic fluoropolymer that has been used commercially since the 1970s. The first large-scale use of extruded ETFE foil in inflated cushions was for the roof of the Mangrove Hall at Burgers' Zoo, in Arnhem, The Netherlands, constructed in 1982 [2]. There has been subsequent development of its material properties, technology and installation systems leading to its wider application in buildings as substitute for glass where high translucency, low structural weight and complex shape is essential [1]. Application of ETFE foil in building envelopes not only reduces overall weight of the building components but also reduces embodied energy by reducing the quantity of materials used and the size and complexity of supporting structures in comparison to glass [3,4]. Integration of ETFE foil in building envelopes allows flexible building geometry, reduces fragility whilst providing good access to daylight and solar radiation.

Similar to any other transparent construction material (e.g. glass) solar radiation penetration through a transparent (or translucent) ETFE foil cushion envelope has an impact on the thermal environment it encloses – positive or negative - by means of its continuous interaction with the external environment. In order to better understand and accurately predict thermal environments in such enclosures continuous field monitoring of a double-layer ETFE foil cushion covered 625m^2 atrium has been carried out since December 2013. A discussion of earlier results can be found in [5] and [6]. Data collected in May, June and July 2014 are analysed, discussed and compared with simulated behaviour here.

2 DESCRIPTION OF ON-SITE MONITORING

The main building of the Nottingham High School is of three-storeys built in 1860. Its central courtyard, previously used as car parking space, was modified and enclosed during the summer of 2009 to form a three-storey high atrium. This atrium is generally used as a dining hall on the ground floor, a café bar on the first floor and a study area on the second floor. The atrium roof, shown in Figure 1, consists of 25 ETFE-foil cushions formed using a fritted top layer and transparent bottom layer of 200µm thick foils covered by a white rain noise suppression mesh. These are fixed within aluminium framing and supported by tubular steel trusses and columns below. Small high windows on the west façade of the atrium are the only means of natural ventilation. These are controlled by the BMS and operate in conjunction with dampers located on top of entrance doors on the north and south sides of the atrium.

Results obtained during the months of May, June and July 2014 analysed and discussed here. Specific primarily overcast days (and nights) and primarily sunny days (and nights) are highlighted. Days with the maximum and minimum total horizontal solar radiation are considered as sunny and overcast days respectively.

Table 1: Description of sensors

Measurement	Sensor type
Air temperature and ETFE foil surface temperature	ϕ0.1 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) connected to dataTaker DT 85 or dataTaker DT 80 data logger
Relative Humidity	Tinytag Plus 2 temperature and humidity sensor
Mean radiant temperature	ϕ0.1 mm K-type thermocouple placed in black globe and connected to dataTaker DT 85 or dataTaker DT 80 data logger

In-situ recording of environmental parameters included internal and external incident solar radiation, internal and external relative humidity, outdoor ambient temperature, and air temperatures at different vertical and horizontal positions in the atrium, external surface temperature of an ETFE cushion and internal surface temperature of two different cushions located on the north-east and south-west parts of the roof. Sensors were as listed in Table 1.

Local weather data was collected from an on-site weather station, located on an adjacent school building roof. The screened thermocouples were connected to DataTaker DT 80 and DT 85 data loggers set to continuously recorded diurnal variations of air temperature at various levels in the atrium and cushion surface temperature at 1 minute intervals. For analysis, data recorded at 5 minute intervals were extracted. A thermocouple placed inside a black globe was used to measure mean radiant temperature. During monitoring ϕ0.1 mm K-type thermocouples (screened) were successfully taped to the ETFE foil surface despite its non-adherent characteristics. The accuracy of surface temperature measurements was validated using thermal imaging.

Table 2: Location and sensor ID of solar radiation and temperature sensors

Sensor ID	Location
TSi 1(a)_NH	Occupied level 1 (Ground floor)
TSi 2 (a)_NH	Occupied level 2 (First floor)
TSi 3 (a)_NH	Occupied level 3 (Second floor)
TSi 4 (a)_NH	Internal Temperature adjacent to ETFE
Ts Loc 1	External foil surface temperature of
Ts Loc 4	Internal foil surface temperature of
OAT	External ambient temperature
ExIR	Incident solar radiation
InIR	Transmitted solar radiation

Figure 1: ETFE cushion roof - external (left) and internal (right)

3 RESULTS AND DISCUSSION

Results obtained during the early summer of 2014 (May, June July) under different sky conditions affecting the internal thermal environment of the atrium are discussed in this section. For analysis of the atrium's internal thermal environment, days were selected when maximum and minimum total solar radiation was observed, being taken as representative of sunny and overcast sky conditions respectively.

3.1 Monitored thermal environment of the atrium

Figures 2, 3 and 4 present air temperature throughout the day for the three occupied levels in the atrium and adjacent to ETFE cushion roof, outdoor ambient temperature, ETFE cushion surface temperature (internal and external), and incident and transmitted solar radiation for two warm sunny days (25th May and 26th June 2014) and an overcast day (28th May 2014). The school was occupied on 26th June 2014 so the impact of the HVAC system has to be considered. However the HVAC system was not operating on 25th May 2014 (a school holiday period) or 28th May 2014 (a weekend). Table 3 presents air temperature range, standard deviation and average air temperatures for the full studied period.

From Figures 2, 3 and 4 it can be seen that at the ground floor (occupied level 1) the air temperature was relatively stable (+/-) 2~3°C and little influenced by outdoor weather conditions. This can be explained by the thermal inertia of the atrium walls and floors, possibly influenced by operation of the HVAC system. The relatively low standard deviation observed for occupied level 1 during the entire studied period presented in Table 3 also indicates the stability of air temperature. Day time air temperature of this occupied level was 3°C~4°C lower than that of occupied level 3 in June and July. Maximum deviation, 11.32°C, was found between TSi 4 (a)_NH (temperature adjacent to the ETFE cushion roof) and TSi 1 (a)_NH (occupied level 1) recorded in the afternoon on the 26th June 2014. Whereas the maximum temperature difference for occupied level 1, 11.3°C warmer than the outdoor ambient temperature, was observed on 25th May 2014 during a clear night. Occupied level 2 was more affected by outdoor weather conditions with air temperature 1°C -2°C higher than that of occupied level 1, with a maximum recorded temperature of 26.6°C, 2.9°C higher than occupied level 1, observed during the afternoon on 26th June 2014. Larger sky view factor, proximity to the translucent ETFE cushion roof and radiant heat from solar radiation affects the air temperature of occupied level 3 significantly. Among the different occupied levels the highest temperature, 27.8 °C, was recorded in occupied level 3 (5.4°C higher than coincident outdoor ambient) on the 26th June 2014. The greater standard deviation also pointed towards the larger variation of temperature range in this occupied level compared to occupied level 1 and 2 throughout the studied period, specifically on clear sunny days. It was also noticeable that in the presence of cloud cover and moving clouds the thermal environment in the upper atrium space reacts rapidly according to the variation of the sky conditions. This was more apparent in the clear sky condition observed in 25th May 2014 (Figure 4).

Table 3: Recorded air temperature range, standard deviation and average air temperature within the atrium during May, June and July 2014.

Month	**May**		**June**		**July**	
Sky condition	Sunny	Overcast	Sunny	Overcast	Sunny	Overcast
Unit	°C	°C	°C	°C	°C	°C
Air temperature range of occupied level 1	18.8-21.8	17.1-20.43	22.08-23.96	21.34-22.6	20-22.9	20.3-23.3
Standard deviation of air temperature (occupied level 1)	0.81	1.13	0.54	0.33	0.94	0.76
Average air temperature (occupied level 1)	20.91	19.26	22.9	22.03	21.37	21.98
Air temperature range of occupied level 2	20.41-23.4	19.62-21.55	22.3-26.62	21.4-24.2	21.9-25.2	23.23-24.8
Standard deviation of air temperature (occupied level 2)	0.84	0.63	1.17	0.7	1.03	0.4
Average air temperature (occupied level 2)	21.59	20.5	23.8	22.62	23.42	23.9
Air temperature range of occupied level 3	20.14-24.73	19.10-20.9	22.04-27.8	21.4-24.7	21.75-25.6	23.48-26.6
Standard deviation of air temperature (occupied level 3)	1.29	0.6	1.6	0.9	1.27	0.6
Average air temperature (occupied level 3)	21.53	19.9	24	22.59	23.27	24.5

During typical overcast days, 28th May, 3rd June and 19th July 2014, in the absence of direct solar radiation the observed air temperature of occupied level 3 was relatively stable, 19-

21°C, 21-23°C, 24-26°C respectively. Figure 5 illustrates the percentage time that the atrium air temperature at each level is within specified ranges (17-26°C, 26-28°C, 28-32°C and over 32°C) for the months of May, June and July 2014. From this figure it can be seen that in June and July 2014 for 3.5% and 7% of the time, respectively, the air temperature of occupied level 3 was between 28°C and 32°C. This temperature range is significantly higher than the comfort range (18°C-26°C).

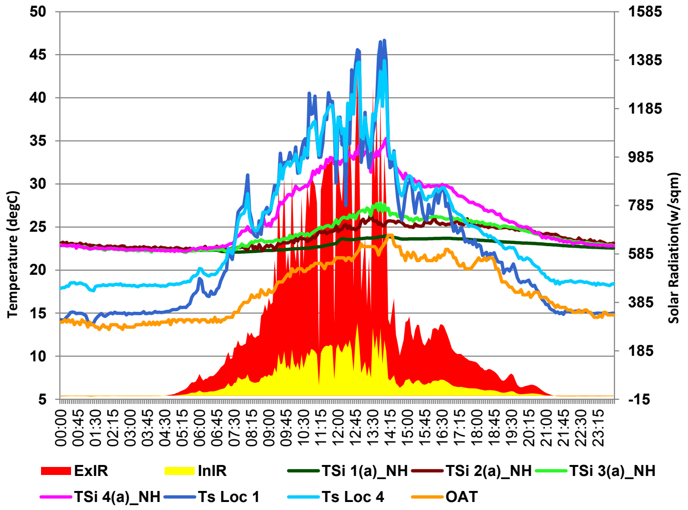

Figure 2: Recorded temperatures and solar radiation for atrium during a sunny day (26th June14)

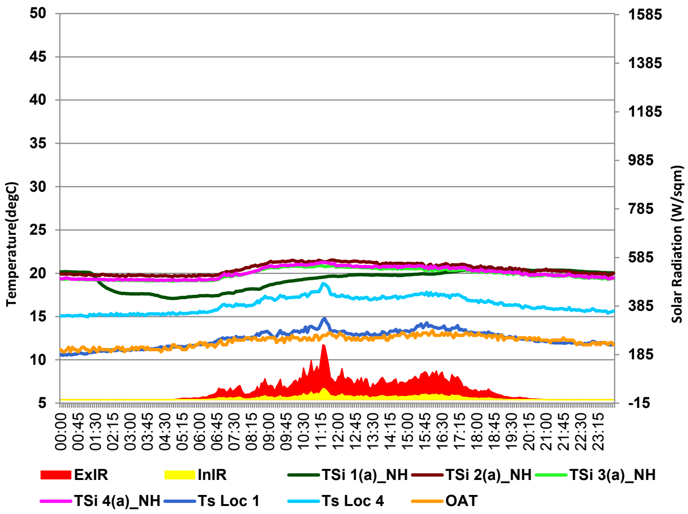

Figure 3: Recorded temperatures and solar radiation for atrium during an overcast day (28th May14)

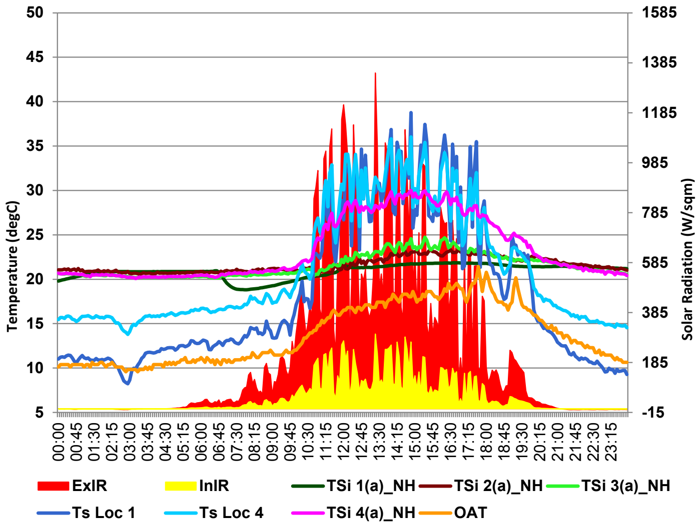

Figure 4: Recorded temperatures and solar radiation for atrium during a sunny day (25th May14)

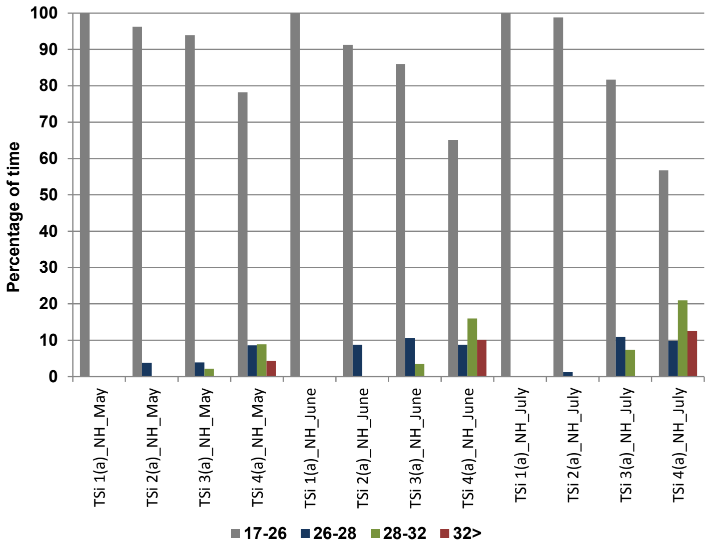

Figure 5: Percentage of time atrium air temperature at each level is within specified ranges 17-26°C, 26-28°C, 28-32°C and over 32°C for the months of May, June and July 2014

3.2 Surface temperature of ETFE foil

In the presence of cloud cover (see Figure 3) the surface temperature of the external foil layer remained close to the outdoor ambient temperature whereas that of the internal foil layer followed approximately the average of adjacent internal air (occupied level 3) and external ambient values. Daytime internal foil surface temperature was on average 7.5°C lower than that of occupied level 3 and 4.5°C above outdoor ambient temperature but the external foil surface temperature stayed within +/-0.6 °C of outdoor ambient temperature. During the overcast night (Figure 3) the internal foil remained on average 3.9°C above outdoor ambient temperature. The external surface temperature coincided with outdoor ambient temperature and approximately 8.3°C below the temperature of occupied level 3.

Under clear sky conditions the ETFE foil surfaces demonstrated more extreme temperature variation influenced by both direct solar radiation and long-wave radiation. At night foil temperatures showed similar behaviour to the overcast sky condition. However, shortly after sunrise, in particular on the 26th June 2014 when there was more intense insolation early in the day, both foils exhibited a more rapid rise in temperature than either the external air or the internal air adjacent to the cushion in occupied level 3. During the middle of the day the internal and external foil surface temperatures tended to converge, with changes in temperature of both generally following the solar radiation intensity profile. In both Figure 2 and Figure 4 it can be noted that, once the foil surface temperature exceeds that of the adjacent air in occupied level 3 the air at that level is heated rapidly forming a stable static layer above the cooler lower atrium levels and inhibiting natural convection. Once direct solar radiation moderated there was a rapid fall in surface temperature of both foils (on both 25th May and 26th June 2014) to resume the overcast sky/clear night condition with external surface temperature similar to (or even below) external ambient temperature.

Diurnal distribution of minimum, average and maximum difference between ETFE foil surface and external air temperature and diurnal distribution of minimum, average and maximum difference between ETFE foil surface and occupied level 3 air temperature in 26th June 2014 is presented in Figure 6.

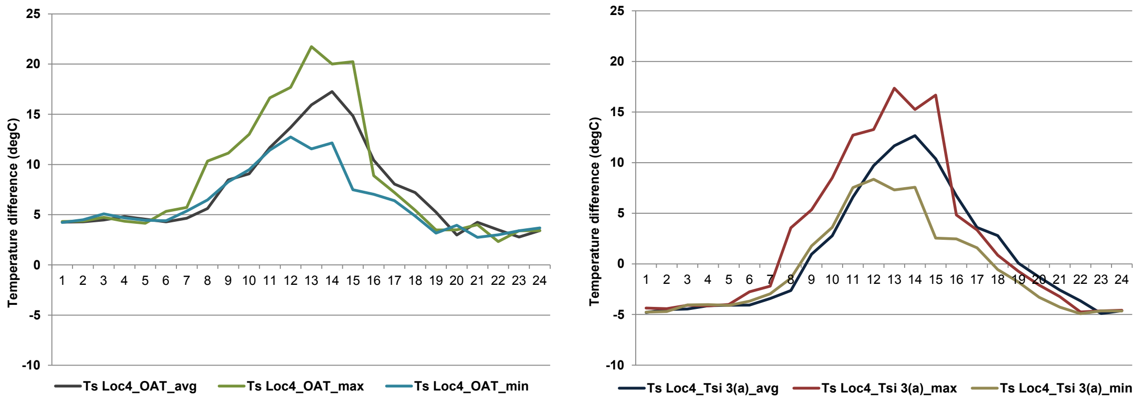

Figure 6: Diurnal distribution of minimum, average and maximum difference between ETFE foil surface and external air temperature (left); Diurnal distribution of minimum, average and maximum difference between ETFE foil surface and occupied level 3 air temperature (TSi 3(a)_NH) (right) 26th June 14

3.3 Simulation of thermal behaviour of atrium

Some preliminary results have been generated using a simulation model developed using the dynamic simulation tool EDSLTAS (version 9.3.2) [7]. The actual site weather data collected on 26th June 2014 was used as input for the simulation. Boundary conditions of model were developed using the manufacturer's data.

Predicted temperatures at different occupied levels in the atrium have been compared with the measured air temperatures. These are presented in Figure 7 where it can be seen that the simulated daytime air temperature agrees reasonably with measured data for occupied levels 2 and 3. However, the simulation appears to underestimate the daytime temperature at both the ground floor (level 1) and immediately below the foil cushions – by up to 5°C. Night time temperatures at all four levels were generally underestimated by the simulation, by around 3 to 4°C. An apparent time lag of around 2 hours can be noted for the increase in temperature of air at the underside of the cushion and the reason for this is currently under investigation. The model is presently being refined in order to predict the thermal environment of the atrium with a higher degree of accuracy.

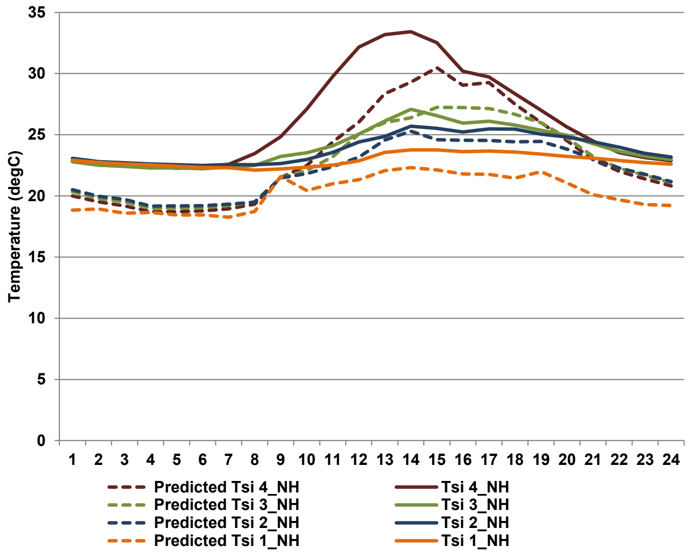

Figure 7: Predicted and measured air temperature at different levels of the atrium (26th June 2014)

4 Conclusions

During clear sunny days significant variation of ETFE foil surface temperature relative to external ambient temperature was observed throughout the monitoring period from May to July 2014. These strong variations in the internal and external surface temperature of the ETFE foil roof coincide with strong positive temperature stratification in the atrium during the day and negative at night. In particular it was noted that the air temperature immediately below the cushions increased rapidly once the foil surface temperature exceeded that of the air and that a stable layer of hot air resulted.

During the overcast day studied both ETFE foil layers were colder than the atrium for the full 24 hours. The thermal environment typically demonstrated a stable internal condition with relatively uniform temperature distribution. Because of low solar gain there was only a small temperature difference between external ambient air and external surface temperature, vertical stratification was found to be very weak during both day and night with an almost uniform temperature within the occupied levels.

Preliminary simulation of the thermal environment of the ETFE foil cushion covered enclosure was inconclusive, with reasonable agreement between predicted and actual temperature distribution for some levels at certain times of the day but poor agreement at other levels and times of the day. Refinement of the simulation model is ongoing.

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