Experimental study on the thermal performance of ethylene-tetrafluoroethylene (ETFE) foil cushions

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Abstract. ETFE pneumatic foil constructions are used increasingly by designers and builders as an alternative to glass in state of the art building envelopes. Low weight, high transparency, mechanical resistance and self-cleaning properties of ETFE may contribute to the overall performance. However, reliable information on the thermal performance of ETFE cushions in building envelopes is scarce, limiting the performance prediction in energy simulations. The present study aims to investigate the thermal performance of air-inflated ETFE foil cushions and evaluates parameters of material properties and design which might affect the thermal transmittance. The paper reports on the experiments conducted to quantify the thermal performance using a climate chamber and full-size mock-ups. Based on available standards, tests were designed to compare the thermal performance of three different ETFE cushion designs, under changing climate conditions. The design variations, including frit prints and switchable shading mechanisms, were tested and compared at hot, temperate and cold weather scenarios. The test series provided detailed results on the thermal performance of ETFE cushions which may be of use for the comparison with the performance of other building components and materials, serve as input for energy simulations and provide a theoretical basis for future developments of novel building envelopes.

Keywords: solar radiation; energy, ETFE, thermal performance, building envelope

1. Introduction

Building light and flexible is a common approach in contemporary architecture. Benefits of saving energy and material while achieving attractive shapes and design features are made achievable with tensioned membrane structures. Pneumatic ETFE foil cushions are now considered state of the art for wide span canopy covers but are also increasingly applied in facades or conceived as a continuous enclosing building envelope. This development calls for new approaches of anticipating the thermal performance of the building envelope in order to meet the evermore demanding needs of reducing the energy consumption of buildings.

ETFE (ethylene-tetrafluoroethylene) is a material with outstanding characteristics of mechanical resistance, light transmittance and environmental performance. Buildings incorporating ETFE have achieved now, after four decades of successful implementation in permanent buildings, a high standard of building excellence and have allowed innovative design solutions to become reality. ETFE has been applied in a large number and variety of building types on a global scale and virtually matches any design brief with great flexibility. An example of a typical ETFE project mastering the complex site requirements for the modernization of a historical building can be seen in figure 1.
It is common practice in the building industry to indicate the thermal performance of components of the building envelope with the U-value or thermal transmittance with the aim to evaluate the energy performance of the whole building in advance of construction. U-values for ETFE building envelopes are frequently cited in the literature and compared to common clear double pane or reflective glazing [1]. Based on standard calculations ETFE cushions are reported to have a comparative or even better thermal performance than common glazing solutions [2]. However, due to the three-dimensional geometry and susceptibility to solar radiation of ETFE cushions, difficulties about the accuracy of the calculated values arise, as standard calculation methods represent the complexity of the heat exchange mechanisms in ETFE cushions only to a limited extent [3]. The experimental determination of the thermal performance appears to deliver a more realistic approach to provide data for a comprehensive energy simulation. In the past, various attempts to determine the thermal performance of ETFE foil cushions with experimental methods have been reported in the literature:

For the Eden Project (2000, St. Austell, UK) a thermal performance test of a ETFE double layer cushion with 200 μm foil, using the hot box method, was conducted and reported by Whalley [4]. Robinson-Gayle investigated later the environmental performance of transparent building envelopes and carried out a number of thermal performance tests on a triple layer ETFE cushion (150 μm - 50 μm - 100 μm) under laboratory conditions [5]. In an investigation into the soiling effects on ETFE transmittance, Mainini et al. [6] also used the hotbox method following ISO 9869 to determine thermal performance of a double layer ETFE cushion with 100 μm foil thickness. In another thermal transmittance assessment, a climatic chamber was used to test a double layer ETFE panel with parallel foils of different thickness (100 μm, and 250 μm) [7]. In a more recent study, which aimed for the thermal characterisation of lightweight building envelopes, again, the hot box method according to ISO 9869 was used to measure in situ and under laboratory conditions the thermal transmittance of a double layer ETFE cushion [8]. Overall, these studies provide evidence that this is the most frequently used method. Based on this conclusion this research campaign sets out to comprehensively investigate in a comparative way the thermal performance of different ETFE foil cushion designs under laboratory conditions. The aim is to determine the heat flux and surface temperatures of ETFE foil cushions under varying climate scenarios, which will allow designers to incorporate the data in future prediction studies for energy performance of buildings.

2. Methodology
To date various methods have been developed and introduced to measure the thermal transmittance of ETFE foil cushions. The methodology of this study was designed on the basis of ISO 9869-1-2014 [9]. Following this method, the heat flux through the samples is measured, which allows one to calculate in combination with surface and ambient air temperatures, the thermal resistance and transmittance for comparison with theoretical derived values. The details of the tested samples and experimental set-up are outlined in the following section.
2.1. Samples
Three ETFE cushions were tested in the climate chamber. All samples measured 1000 mm by 1000 mm with a rise of 100 mm of the main section curvature on each side of the centre plane, in a state of full inflation. The air filled volume is approximately 90 litres at a nominal pressure of 300 Pa. The cushion edges were clamped into an extruded aluminium profile and mounted on a structural frame to support the cushion and withstand tension forces when fully inflated. The whole unit measured 1200 x 1200 mm. All samples are composed of extruded ETFE foil with a thickness of 200 μm and a weight of 350 g/m². The detailed sample specifications are listed below:

- Sample 1 is composed of two layers of clear ETFE foil.
- Sample 2 is composed of two layers, one clear and one fritted, with a hexagon pattern of approximately 71% surface cover in a standard silver ink with a print density of 28%.
- Sample 3 is composed of three layers, one clear and two, with a square pattern of approximately 74% surface cover in a standard silver ink with a print density of 28%. The printed layers are shifted in a way that the printed areas of one layer overlap with the clear areas of the other. This makes it possible to modify the transmittance of the cushion, switching from open to closed state, by changing the position of the printed middle layer with air pressure.

2.2. Climate Chamber
A large environmental test chamber (fig. 2) was used to create different temperature scenarios. The climatic chamber is able to independently control the temperature and humidity of two walk-in-rooms, while the test samples are installed in-between. This enables one to simulate indoor and outdoor conditions with steady state or cyclic climate conditions.

2.3. Experimental Set-up
The samples were mounted in a separating insulated dry-wall between the two rooms of the climate chamber and shielded from convective effects by baffle walls on each side. The cushions were inflated and equipped with calibrated T-type thermocouples and heat-flux-meters. A total of eighteen temperature sensors were distributed in a square pattern, of three by three units, and attached to the inner and outer layer of the cushion. Three heat-flux meters were attached on a centred vertical axis over the outer layer of the cushion (fig. 3). An additional fourth heat-flux meter was attached at the centre of the inner layer for measurement control. The homogenous distribution grid of the sensors allowed any variations in heat-flux or surface temperature over the curved sample surface to be detected. The air temperature was measured with temperature sensors within the 500 mm baffle zone on both sides.
2.4. Testing Scenarios
Thermal performance of lightweight structures is largely dependent on climate conditions. In order to comprehensively investigate the heat flux through ETFE cushions for varying conditions an array of testing scenarios was established. Departing from the standard boundary conditions for determining the thermal transmittance based on EN 673:2011 [10] the samples were tested under five scenarios with a varying range of mean surface temperatures and surface temperature differences (table 1). To achieve these temperature scenarios the two rooms of the climate were cooled and heated with HVAC units to pre-calculated temperatures. The surface temperatures were monitored continuously until steady state of the target values was achieved. Then the transversal heat-flux through the samples was measured. The results will be presented and discussed in the following section.

Table 1. Testing Scenarios

| Surface Temperatures [°C] | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---------------------------|------------|------------|------------|------------|------------|
| Outside                   | 6.3        | 5.0        | 2.5        | 7.5        | 0.0        |
| Inside                    | 13.8       | 15.0       | 17.5       | 22.5       | 15.0       |
| Difference                | 7.5        | 10.0       | 15.0       | 15.0       | 15.0       |
| Mean                      | 10.0       | 10.0       | 10.0       | 15.0       | 7.5        |

3. Results & Discussion
On continuation the preliminary results obtained from the heat flux measurements on the three cushion samples are outlined. The values obtained for the heat flux at different positions of the sample surface showed a variation according to the section height and width of the cushion at the measurement positions. For a more general analysis, these values were averaged and combined into a mean heat flux value for each sample and scenario. From the graphs in figures 4 and 5 it can be seen that all cushion samples showed a similar trend in the magnitude of heat flux for all temperature scenarios, ranging from the lowest heat flux of 38.4 W/m² to the maximum of 96.2 W/m², for sample 3 and 1 respectively. However, there was a significant difference between the three samples regarding the amount of energy transferred with a variation of approximately 5 to 10%, as can be seen in figure 4 and 5. Sample 1 presented the highest heat flux rate in all tested scenarios followed by sample 3 in closed mode, then sample 2 and with the lowest heat flux sample 3 in open mode. It seems possible that these results are due to the different emissivity of the printed and unprinted foil surfaces. Another important finding was that the mean temperature between the inner and outer surface had only a relatively small influence on the heat flux (fig. 4) the variation of the temperature difference had a larger impact with a significantly increasing heat flux at a higher temperature difference. While this result is not surprising from a physical
point of view it illustrates the high susceptibility of the thermal performance of pneumatic foil cushions to climatic conditions. The present findings seem to be consistent with other research which found a similar behaviour of other cushion designs. However, with the relatively small sample size, in comparison to usual building applications of ETFE, caution must be applied, as the findings might not be transferable without adjusting the measured values to the corresponding scale of the structure.

4. Conclusions
This study set out to investigate the thermal performance of printed and unprinted ETFE foil cushion designs under varying climate conditions. The most obvious finding to emerge from this study is the high susceptibility of the thermal performance of pneumatic foil constructions to changing conditions of in-/ and outdoor temperatures. This is of significance for the design of building envelopes using this type of construction and material. The comparison of the three distinctive designs also showed that the frit print reduces the heat flux of the whole cushion, and smart frit prints allow one to effectively switch between higher and lower heat flux states. The present study confirms previous findings and contributes additional evidence that suggests that reflective frit prints have a large impact on the overall thermal performance of ETFE foil cushions. Adaptive technologies like the switchable smart frit might offer even bigger benefits as they are capable of moderating effectively the heat flux under different climate conditions especially between high and low solar radiation. A further study with more focus on heat transfer through solar radiation is therefore suggested.

5. References

[1] Chilton J 2013 Lightweight envelopes: ethylene tetra-fluoro-ethylene foil in architecture. P I CIVIL ENG - Construction Materials 166 CM6 343–57
[2] Lippke R 2009 Folien als Transparente Elemente in der Fassade mechanische und Bauphysikische Eigenschaften (Berlin: Technishe Universität Berlin) p 272
[3] Afrin S 2016 Thermal Performance Analysis of ETTE-foil Panels and Spaces Enclosed with ETTE-foil Cushion Envelope (Nottingham: University of Nottingham) p 333
[4] Whalley A, Grimshaw & Partners N 2000 The Eden Project glass houses world environments In: Barnes M, Dickson M Widespan Roof Structures (London: Thomas Telford books) pp 75 - 84
[5] Robinson-Gayle S 2003 Environmental Impact and Performance of Transparent Building Envelope Materials and Systems (London: Brunel University) p 306
[6] Mainini AG, Poli T, Paolini R, Zinzi M, Vercesi L 2014 Transparent multilayer etfe panels for building envelope: Thermal Transmissivity Evaluation and Assessment of Optical and Performance Decay due to Soiling Energy Procedia 48 1302-10
[7] Martin BAJ, Lau B, Beccarelli P, Chilton J, Wu Y 2015 Modular transparent etfe panels for building envelopes thermal transmittance assessment and evaluation Proceedings IASS 2015 Amsterdam Symposium: Future Visions 1-9
[8] Dimitriadou E A 2015 Experimental Assessment and Thermal Characterisation of Lightweight Co-Polymer Building Envelope Materials (Bath: University of Bath) p 260
[9] ISO BS ISO 9869-1 2014 Thermal insulation - Building Elements - In-situ Measurements of Thermal Resistance and Thermal transmittance - Part 1- Heat Flow Meter Method p 48
[10] CEN BS EN 673 2011 Glass in building - Determination of Thermal Transmittance (U value) - Calculation method p 22

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