Extreme Soft Skins: Multilayered ETFE for Challenging Environments

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Abstract

ETFE has been rapidly expanding its presence in the building industry, finding its application on all parts of the envelope, especially skylights due to the superior light transluence (Monticelli, 2015). Recent technological developments of multi-layered ETFE systems coupled with advanced coatings have altered their performance and boosted their potential for applications across all latitudes. The paper presents the optical and thermal characterization of multi-layered ETFE foils performed at the TextilesHUB - the Interdepartmental Research Laboratory at Politecnico di Milano. Studies include ETFE with advanced silk-screen printed coatings and coating patterns for various real case projects in challenging environments, covering both cold and hot extremes. Special focus is placed on hygro-thermal analyses to inform the design of the frame to eliminate potential condensation caused by the high-temperature difference between both sides and very low thickness at the edge of the ETFE cushions, where all layers converge into framing gasket. Moreover, the paper presents an optimization process for improving performance of ETFE layer compositions to mitigate high environmental stresses, provide optimal indoor comfort and reduce energy demand. Finally, we present achieved performance levels of different ETFE systems implemented in three projects in Sankt Petersburg, Milan and Manama and discuss possibilities for future improvements.

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1. Introduction

The early presence of ETFE in the building industry was characterized by its temporality and lightness. Majority of ETFE structures were auxiliary and temporal buildings, mostly for limited and not extended occupant use. Moreover, the unrivaled light-weightiness of the construction, only one hundred of the equivalent construction in glass, has enabled creation of large span structures. As a consequence, the cost of such constructions was also much lower than those made of glass. However, in this phase of ETFE development, its minimal thickness and lack of spectrally-selective coatings in the two-layered system limited its optical and thermal properties and range of suitable climates (Chilton, 2013). Recent technological developments of multi-layered ETFE systems coupled with advanced coatings have altered their performance and boost their potential for applications across all latitudes. Since then, ETFE has been rapidly expanding its presence in building industry, finding its application on all parts of the envelope, especially skylights due to the superior light translucence of 90-95% (Monticelli, 2015).

The paper presents the optical and thermal characterization of multi-layered ETFE foils with advanced silk-screen printed coatings and coating patterns for three real case projects in challenging environments, covering both cold and hot extremes. Performance levels of different ETFE systems implemented on projects in Sankt Petersburg, Milan and Manama are shown. Moreover, the paper presents an optimization process for improving performance of ETFE layer compositions to mitigate high environmental stresses, provide optimal indoor comfort and reduce energy demand. Special focus is placed on hygro-thermal analyses to inform the design of the frame to eliminate potential condensation caused by the high-temperature difference between both sides and very low thickness at the edge of the ETFE cushions, where all layers converge into framing gasket. The paper proposes and discusses potential solutions. In addition, the paper explains challenges of structural framing and gaskets detail design of multilayered ETFE to accommodate all layers and widen edge of the cushion thickness to improve u-value in these areas.

2. Methodology

The paper presents a methodology for addressing arbitrary complex thermal and optical requirements and consequently achieving high performance of the ETFE systems. Three case studies were chosen to demonstrate the range of climates and suitable ETFE structures. All three structures are atrium roof coverings in large projects located in Manama Bahrein; St. Petersburg, Russia; and Milan, Italy representing hot desert, warm-summer Mediterranean and Savanna climates respectively according to the Köppen classification (Köppen, 1884) Figure 1. Despite a large variation in environmental loads, with a range of average high summer
temperatures from 39°C to 23°C and winter from 20°C to -4°C, annual global horizontal solar irradiation from 2100KWh/m² to 900KWh/m², each project follows a general methodology that balances optimal and thermal properties.

Figure 1: Climate data of cities of case studies

The methodology starts with a project brief that specifies required thermal transmittance or u-value and Solar Heat Gain Coefficient (SHGC) or g-value for a Total Fenestration Product (TFP)(NFRC, 2013). TFP is composed of Frame, Edge of Glazing (EOG) and Center of Glazing (COG) parts, where the latter is of much higher significance due to the size of ETFE cushions that may be much larger than those in the glass counterpart. TFP performance is calculated according to the standards ISO 9050, ISO 15099, EN 410 and EN 673 using validated Optics6 and Window 7.4 for COG and EOG values, while the frame has been calculated in Therm 7.4. The software is provided by the Lawrence Berkeley National Laboratory (LBNL). ETFE cushion curved surface geometry structure has been simplified to parallel flat surfaces in modeled layer configuration using a value of 100mm as an average distance of the air gap between ETFE layers that do not influence u-value. EOG area used an air gap of 20mm and has perimeter offset of 5cm. A typical frame profile and thermal analysis are shown in Figure 2. The figure also shows a schematic diagram of TFP components and the following formula used to determine TFP u-value. Environmental conditions were set to NFRC 100-2010 unless specified otherwise like in the Case Study 3 – Extreme Cold Climate: Lakhta Center, St. Petersburg, Russia. The emissivity of all ETFE surfaces was set to 0.84, with exception of coated surfaces with an emissivity of 0.57. Thermal conductivity of ETFE was set to 0.24W/mK. Since most of the currently available ETFE foils have similarly mentioned emissivity, u-value of multilayered ETFE systems will be dependent only on a number of layers, assuming exterior-facing foil is always coated. The selection process for reaching required u-value is therefore straightforward. Two-layered ETFE will have u-value of 2.6W/m²K, three-
layered 1.8 W/m²*K and four-layered 1.3 W/m²*K. Further improvements of thermal performance are possible either by adding more layers or changing spectral-selectivity of coatings. However, five-layered cushions and IR-cut coatings with the emissivity of 0.4 and below are still in experimental phases and not yet commercialized.

When the number of layers is defined, the process continues with an optical characterization of materials to determine g-value. This part is not straightforward as there are many parameters influencing optical behavior to various extents. Three main optical performance parameters are: foil thickness, coating type and percentage of the coated area, while pattern type is a visual parameter that affects aesthetics and may be determined by other stakeholders. In most of the cases, pattern type, percentage of the coated area and coating type are all predetermined by the ETFE foil producers to cover all range of g-values from 0 to 1. Each of the parameters has its code and each ETFE foil name is composed from parameters codes. In that way, selection filters may be applied to acquire a selection of foils with desired parameters and possible alternatives of other parameters. For standard ETFE foils, producers provide optical and thermal specifications, while custom products may be produced on demand. Additionally, producers may present spectral curves or provide optical data showing Transmittance (T), Reflectance on the front (Rf) and back side (Rb) in Ultraviolet (UV), Visible (VIS), Near-Infra-red (NIR) and Far-Infra-Red (FIR) parts of the spectrum. Optical data of ETFE foils represent a necessary step in determining multilayered ETFE system performance. Due to the very low variability in the optical performance of uncoated foils, inner-facing and middle foils are characterized with a standard spectral curve of ETFE. For uncoated foils, it is possible to adjust the spectral data to
account for different thicknesses. For exterior-facing foils, there are two types of inputs that determine further procedures. Since for ETFE foils with a very small pattern, where individual geometries are 3-4mm and less, it is not possible to perform optical characterization only through coated parts, optical data of such foils are representative for the whole surface. Alternatively, in case of larger size patterns, optical data represents only the coated part. In this case, the final optical performance of the ETFE system is determined by calculating two systems, one with coated exterior foil and one for uncoated, that are later linearly interpolated based on a percentage of the coated surface. In order to calculate the performance of multilayered systems, process use spectral data, obtained through laboratory spectral characterization of samples using UV/VIS/NIR spectrometers, from producers or measured at the ThermALab at the Energy department of Politecnico di Milano. Measurements are performed at the normal incidence and contain hemispherical T, Rf and RB at 5nm wavelength increment for the wavelength range of 380nm-2500nm. Before importing into LBNL Optics, data was processed to comply with the required data structure. Spectral data of all samples were then stored in user-defined libraries under International Glazing Data Base (IGDB) that could be accessed by LBNL Window. Detail ETFE system optical and thermal characterization of COG and EOG was performed using standard procedures. Where coating and pattern types allowed different combinations, options were computed in Excel and then for the same performance levels, final selection has been chosen according to the visual criteria.

The last component in TFP, frame, is calculated separately as it does not interfere with other components. Since ETFE cushion has a variable thickness, that decreases towards frame where it gets to zero, thermal properties in EOG areas are the most critical points of the construction Figure 3 (left). Moreover, since the thermal impact of the frame in TFP is a quite small, more important aspect in frame simulation is hygro-thermal, or water vapor transfer and condensation risk. This risk is higher in humid climates with higher dew point temperature. These climates require special improvements to the fixing detail - Figure 3 (middle and right). This can be done either by an increasing distance between the layers (proposal 1) or increasing the size of the EPDM profile to extend contact length with ETFE (proposal 2). In both cases, there is no zero path length with a high-temperature difference between exterior and interior that creates condensation on interior surfaces stimulating fungal growth.

**Figure 3: Improving weak spots in multilayered ETFE joints for extreme climates**
3. Case Study 1 – Extreme Hot Climate: Shopping Mall, Manama, Bahrein

The first of the case studies represent a project - Figure 4 located in extreme cooling dominated climate with the average dry bulb temperature from 6°C to 30°C and annual global solar irradiation of 2100kWh/m². Such a high environmental load required high thermal and optical protection. U-value of 1.31W/m²K was chosen to be adequate, that corresponds to the four-layered ETFE system - Figure 5. Similarly, the project required low g-value and since ETFE was placed on the roof of the shopping mall corridor, there were no constraints regarding optical clarity. The pattern with one of the highest coverages was Hexagon, with the 89% covered with silk-screen printed silver coating. This pattern allowed further adjustment of the coating type for fine-tuning g-value, one with high spectral selectivity and one with the standard.

Figure 4: Corridor of the shopping mall in Manama (©Taiyo Europe MakMax)

Figure 5: Multilayered ETFE properties of the shopping mall in Manama (extract of the report done by authors for Tai Europe MakMax)
4. Case Study 2 – Moderate Climate: CityLife, Milano, Italy

The second case study - Figure 6 is located in moderate heating dominated climate with the highest average summer dry bulb temperature of 39°C and annual global solar irradiation of 1400kWh/m². Moderate environmental loads required average thermal and optical protection and therefore three-layered ETFE system with U-value of 1.82 W/m²K was used - Figure 7. Again, there were no constraints regarding optical clarity, yet g-value requirements were still high. In the coverage range from 70% to 80%, Negative dots in combination with dense coating provided optimal g-value of 0.34 and Tvis of 30%. The ETFE system was additionally successfully tested with raytracing simulations against a temporary increase of concentrated solar radiation caused by highly reflected glazing of the curved Zaha Hadid tower.

Figure 6: Atrium of the shopping mall in CityLife complex (©Taiyo Europe MakMax)

Figure 7: Multilayered ETFE properties of the shopping mall in CityLife complex (extract of the report done by authors for Taiyo Europe MakMax)
5. Case Study 3 – Extreme Cold Climate: Lakhta Center, St. Petersburg, Russia

Contrary to the previous two case studies, this project - Figure 8 is located in extreme heating dominated climate with the average dry bulb temperature from -4°C to 23°C and annual global horizontal solar irradiation of just 900kWh/m². Again, high environmental loads demanded U-value of 1.31W/m²K and four-layered ETFE system like in the case of Manama. Since this project is located in Russia, standards required modifications of boundary conditions to account for extremely low temperatures. All parameters followed standards ISO 15099 and NFRC 100-2010 (Wind speed: 5.5 m/s; Indoor air temperature: 21°C; Outdoor air temperature: -18°C; Irradiation on surface: 0 W/m²) except for outdoor winter temperature that was set to -26°C according to the client’s requirements. Client in coordination with contractor performed experimental validation studies on a real scale prototype using the dual climatic chamber to verify simulation results. Values obtained by testing showed a minor discrepancy in comparison to the simulation ones. The project did not specify high requirements for g-value as solar radiation in this climate is considered beneficial. Unfortunately, the client did not allow the publishing of material and therefore there is no figure demonstrating the results of the study.
6. Conclusion and future works

Despite the advances in the building simulation tools, there are still challenges ahead in optical, thermal and computational fluid dynamics simulations, particularly when handling complex free-form geometries, thin materials and coatings. There are many levels of uncertainties that influence simulation accuracy. This can be caused by the simplification of geometry, materials and boundary conditions, reduction of dimensionality and parameter sets, thus neglecting angular dependency of system properties and multi-physics behaviour of the system. Therefore, future work will be focused on exploring more robust simulation approaches able to handle arbitrary complex cases with controllable deviations. In particular, the area of research will include 3-dimensional multi-physics simulation of complex geometries and materials including optical, thermal and CFD simulations. Furthermore, research will explore the dynamic and adaptive behaviour of the ETFE systems and it’s potential to mitigate seasonal environmental loads. A particular area of interest will be to study the angular-dependent influence of ETFE cushion curvature, material properties, air pressure states, turbulent air-flows inside ETFE cushions and middle layer movement on the optical and thermal behaviour of multi-layered ETFE systems.

On the other hand, future research will also cover simple and efficient simulation models with reasonable accuracy. In this way, research will explore the whole range of simulation tools and aim to assess accuracy for various Levels of Details (LODs) and consequently creating more effective ETFE workflows and processes. Knowing accuracy-LOD correlation for each design phase will allow greater confidence in exploring design options in early phases and gradual accuracy increase as approaching detailed design phases.

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References


