

Computational modelling of the thermal behaviour of an ETFE cushion using IES

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ABSTRACT: Ethylene Tetrafluoroethylene (ETFE) membrane is a recent popular option for the building industry as a sustainable alternative to glazing; typically assembled into cushions to retain structural stability and improve thermal resistance. ETFE is often absent from material libraries found in energy simulation tools, frequently requiring designers to use glass material properties in substitution, potentially leading to errors when calculating the energy consumption of a building employing ETFE cushions. This study investigates the differences in performance between glass and ETFE; specifically in relation to energy used for space heating. Integrated Environmental Solutions (IES) is an engineering and environmental performance software tool used to estimate the energy performance of buildings. This study uses experimental data combined with IES simulations to determine the energy consumption of a simple building model. The results of this research provide information to create a profile for ETFE to be used with IES or similar simulation software.

1 INTRODUCTION

Ethylene TetraFluoroEthylene (ETFE) is a melt-processible fluoropolymer, belonging to the sub-category of polymer materials called thermoplastics (Kopeliovich, 2011). The material is typically extruded in the form of a membrane which is then assembled to cushions of two to five layers and welded around the edges (LeCuyer *et al.*, 2008). Air valves are fixed on the cushions. The valves are connected to an air pump system that provides the cushion with a constant air pressure of 250-700 Pa to obtain its structural stability and thermal resistance (Robinson-Gayle *et al.*, 2001).

ETFE cushions have been examined in the pursuit of a replacement to glazing, as a solution to the downsides that are associated with its use; such as its fragility, weight and behaviour towards light and heat transmission (Clarke *et al.*, 1998; Robinson-Gayle *et al.*, 2001). If uncoated, glass presents high transmission of near Infra-Red radiation, which leads to an increase of solar gain and a consequent need for cooling in warm conditions. At the same time, uncoated glass presents a low reflectance of far Infra-Red radiation which leads to an increase in heat loss and a related rise in heating requirements during cold weather (Brauer, 1999). The excessive use of glazing also increases the embodied energy and the cost of a supporting structure. Furthermore, the geometry of the building is often an obstacle to the use of glass.

The structural benefits of ETFE cushions in comparison to glass can be summarised to its lower weight, the ability to reach larger spans and freedom of form. Moreover, ETFE membranes are insensitive to deformations of the primary structure, UV resistant, have low maintenance costs such as cleaning and low hazard potential in the event of a fire, explosion or windstorm (Schween *et al.*, 2007).

For a typical thickness of 200 μm a single ETFE film weighs below 3.5 kg per m^2 ; a much lighter weight than the glazing required covering the same area, therefore reducing the embodied energy of manufacturing and transport to 1% of that associated with single glazing. The

lighter weight of the membrane also results to the requirement of a lighter supporting structure than that used in a glass structure, thus reducing cost and energy demands (LeCuyer *et al.*, 2008; Robinson, 2005).

ETFE film is transparent to long-wave radiation. The transmission of long-wave radiation in the case of the cladding unit will depend on the temperatures of the glass panes and their surroundings. Depending on the orientation of the material in relation to the temperature difference between the interior and exterior, the occurring long-wave radiation flux will be inwards or outwards respectively (Poirazis *et al.*, 2010).

ETFE cushions cannot be treated like glass while performing an energy study on its thermal performance. At present there is no available information for the quantification of the long-wave radiation transmission through ETFE cushions (Poirazis *et al.*, 2010). A previous preliminary study by the authors aimed to amend this issue by using the results of an experimental study on the thermal response of a single ETFE membrane cladding unit, alongside a single glass pane cladding, exposed to the same external conditions and supported by the same internal condition regulating mechanism (Dimitriadou *et al.*, 2012). The experiment was refined and repeated at a bigger scale, using a double layer ETFE cushion alongside a double pane glass unit. The present work uses Integrated Environmental Solutions (IES) to reproduce the experimental conditions and results. The result of this research is to determine the necessary adjustments that must be made and the factors to be taken into account when using IES to estimate the energy consumption of a building using one or more ETFE cushions as cladding.

2 EXPERIMENTATION

2.1 Experimental setup

The physical experiment took place using two insulated boxes covered by a two-layered inflated ETFE cushion and a double glazed unit respectively. Both boxes were exposed to the same external conditions. The measurements examined in this study were recorded between the 30th of February 2013 and the 06th of April 2013 under a variety of weather conditions. The structures were located on the roof of the Department of Architecture and Civil Engineering building at the University of Bath (51.38°N, 2.36°W), in Southwest England.

The boxes enclosed a volume of 900 mm height, width and length, with walls and floor made of a single layer of 100 mm PIR foam insulation. The assembly was held in place externally by a wooden frame and the edges were sealed with the use of insulating polyurethane spray foam. Thermal imaging was used to detect areas of excessive heat loss and enhance the insulation around these sensitive areas. Figure 1 and Figure 2 present the experimental setup.



Figure 1. Experimental set-up



Figure 2. The ETFE cushion (left) alongside the double glazed unit (right)

The ETFE cladding unit comprised of a two-layered cushion with dimensions of 900 mm by 900 mm. The cushion membrane had a thickness of 200 μm and the internal side of the cushion was covered by a reflective dotted silver frit. The ETFE unit was prefabricated and supplied by

Vector Foiltec and was inflated to 220 Pa using a Michelin 12250 12 v Digital Tyre Inflator Air Compressor. The glass cladding was comprised of an uncoated, un-toughened double glazed unit of 900 mm by 900 mm and a composition of 4 mm glass – 6 mm air gap – 4 mm glass.

A 100 mm Vent-Axia Silhouette Fan with shutters was used in each box to assist the controlled ventilation of the experimental unit and resolve condensation issues at a maximum extraction rate of 26 l/sec. The fans in both boxes were running continuously and maintained interior relative humidity levels below 60 % for both boxes. The air was extracted from the main box covered with the cladding material, introduced through ducts into auxiliary boxes that assisted in the drying of the air and then was re-introduced in the main box. The fans operated constantly, maintaining a steady interior environment.

The extracted air travelled through plastic ventilation tube of 100 mm diameter, enveloped in a 25 mm thick layer of sheep's wool insulation and surrounded by an external reflective flexible tube of 150 mm diameter. The tube system was connected in an air-tight manner to a separate external box constructed from 100 mm PIR rigid foam insulation holding 285 g of loose desiccant silica gel in each box. The silica gel was dried out prior to weighing and installment in the boxes. After being introduced to the desiccant boxes the same air is then re-entered to the experimental boxes to avoid heat loss through a fitted outlet with shutters.

Each box enclosed two tubular heaters of 655 mm length and 80 mm diameter, with a heating capacity of 120 Watt each. The energy consumed by the heaters was measured using Elster A100c electricity meters. Pulsed output was recorded using Grant SQ2010 Data Loggers. The number of pulses was recorded at 5 minute intervals.

Two K-type thermocouples were located on the North-facing wall and the cladding of each box to record surface temperatures. The surface temperatures were measured with the use of a Grant SQ800 Data Logger. Each box also housed air temperature, black bulb radiant temperature and humidity sensors monitoring interior conditions. Air temperature and black bulb radiant temperature were recorded using a Grant SQ2010 Data Logger, whereas humidity was measured with the use of a Tinytag Data Logger.

2.2 Calibration

Prior to the conduction of the main experiment, the calibration of the boxes took place with both experimental units covered by a 12 mm plywood sheet, concealed with a layer of white, waterproof, non-reflective paint. The calibration process took place throughout the period between the 10th of January and the 18th of February 2013. Both boxes were exposed to the same short-wave and long-wave radiation and external air temperature conditions and bared the same heating, ventilation and recording equipment, placed in the same location.

The box that would later be covered with the ETFE cushion was situated on the South of the box that would later be covered with glass and was therefore more exposed to the prevailing winds of the area. This resulted to a greater heat loss and called for the use of adjustment coefficients on the measured data to match the trend describing the interior thermal conditions and the co-responding energy performance of the glass box. After the calibration of the measured results, the two boxes covered by wood presented an identical thermal behaviour and energy consumption, which allowed the following recordings under the ETFE cushion and the glass unit to be evaluated on a comparable basis.

2.3 Weather file adaptation

External air temperature was monitored in the same location of the experiment. Additionally, a Kipp & Zonen CMP3 pyranometer and a CGR3 pyrgeometer were used for the measurement of the corresponding incident shortwave and long-wave radiation. The pyranometer was adjusted to the geographic location of the 6 East building on the University of Bath campus and recorded both global (direct) and diffuse radiation. Furthermore, relative humidity, wind direction and velocity and barometric pressure were measured on the same location.

The local weather recordings were used to create a weather data file for use in the subsequent IES simulations. The direct normal radiation and cloud cover values were derived according to the IES-VE ApacheSim Calculation Methods (IES-VE, 2013; Kipp&Zonen, 2012).

3 IES MODELING

3.1 Model setup

This section describes the process that was followed for the representation of the physical model in a digital form. The material surface emissivity values were not the default ones corresponding to the used materials but were inserted manually, as the walls of the boxes were painted for protective purposes.

Regarding the implementation of the cladding units, the material properties for the glass unit were taken by default by the IES library, with the exception of the surface emissivity which was considered low and was supplemented using the online database on glass properties provided by the Lawrence Berkeley National Laboratory (LBLN, 2013). The values used for the ETFE unit were taken from the Vector material properties sheet for Texlon®, the Teflon® material properties sheet by DuPont and personal communication with Vector Foiltec (DuPont, 2012; Vector, 2012; Vector, 2013). Table 1 presents a summary of the material properties used to describe both cladding materials.

Table 1. IES model – description of cladding.

	Glass unit			ETFE cushion		
	Clear float glass	Gas (air)	Clear float glass	ETFE membrane (outside layer, clear)	Gas (air)	ETFE membrane (inside layer, dot matrix 65 %)
Thickness (mm)	4	6	4	0.2	40	0.2
Conductivity (W/mK)	1.06		1.06	0.23		0.23
Convection coefficient (W/m ² K)		4.16			2.613	
Resistance (m ² K/W)		0.127			0.163	
Solar transmittance	0.82		0.82	0.911		0.54
Outside reflectance	0.07		0.07	0.08		0.33
Inside reflectance	0.07		0.07	0.08		0.34
Refractive index	1.526		1.526	1.4		1.4
Outside emissivity	0.92		0.92	0.82		0.81
Inside emissivity	0.92		0.92	0.82		0.57

The ETFE cushion could not be implemented as a curved surface and was therefore represented by two parallel flat surfaces. Furthermore, the distance between the two ETFE layers had to be increased to 400 mm in contrast to the 200 mm maximum distance of the actual cushion at the peak of its camber in order to reach the desired U-value for an ETFE cushion as it was specified by the Vector Texlon® material properties sheet (Vector, 2013).

ETFE membrane was essentially treated by IES as a double glazed unit with different properties. The U-value for the glass unit was 3.6 W/m²K alone and 4.0 W/m²K with the frame. The U-value for the ETFE cushion was 2.9 W/m²K alone and 3.3 W/m²K with the frame.

The function of the fans was not implemented in the IES model. Although useful for energy applications, the building simulation of indoor air movement through the use of simulation software such as IES is limited. For this reason, the simulation concerning the internal conditions of the experimental unit including the main box, the auxiliary ventilation box and the ducts is simplified and the thermal and energy calculations are performed considering the summary of the boxes and ducts as a uniform space in steady-state (Clarke, 2001). A simulation using Computational Fluid Dynamics (CFD) will be performed in the future to resolve this issue. In the present investigation, the energy performance presented will concern only the heating requirements of the space, excluding the energy consumed for the function of the fans.

3.2 Considerations

Regarding the design of the experimental units using IES, the ducts had to be represented in rectangular form as IES converts curved shapes into a series of flat plane surfaces. For the same reason the camber of the ETFE cushion could not be accurately represented. The simplification of the curved surface of an ETFE cushion to a flat plane has implications with regards to radiative heat transfer due to differences in view factors, since each point of the cushion surface is at a different orientation relative to the radiative source. However this simplification is expected to have little impact given the limited curvature of the ETFE cushion and future work aims to investigate more realistic geometry through finite element analysis methods.

3.3 Model adjustment

This section discusses the process followed to adapt the IES model to the physical model for the ETFE box. Air infiltration was added to the IES model as the physical model did not achieve complete airtightness. Energy consumption calculations were performed and the suitable amount of air infiltration was selected through trial and error in order to reach the correct model providing with a simulated energy performance that was a match to the real-life energy measurements. The selected amount of air infiltration required for both boxes was 2.0 l/s.

Air infiltrations of various levels were simulated until a best fit to the experimental data was achieved. A linear regression was performed for each simulation and the regression with the best fit was ultimately selected as the representative option. This process was first performed for the glass box, considering that all other properties of that box were already known. Using this as a basis, the same digital model of the box was then covered with the ETFE cushion, in which case an energy and internal condition simulation took place. The calculated results were compared to the real-life measurements.

4 RESULTS

4.1 Physical experiment measurements

The heaters enclosed in each box were set to maintain the internal air temperature at 19 °C. The total measured energy consumption due to heating of the ETFE box throughout the period under examination was 12.2 kWh, slightly lower than the equivalent 12.4 kWh recorded for the glass box.

The range of air temperatures recorded in the ETFE box varied between 18 and 50 °C and the range of radiant temperatures varied between 17 and 55 °C. At the same time, the range of measured air temperatures inside the glass box spread between 17 and 54 °C, whereas the measured radiant temperatures ranged between 17 and 62 °C.

The high measured internal temperature values were recorded under clear sky conditions with a high solar input, leading to overheating of the boxes as no cooling system was installed. Both boxes were steadily maintained at interior conditions close to the desired set point of 19 °C under cloudy skies during night and day for the periods of interest i.e. heating period.

The recorded lower measured air temperatures of the ETFE box can be associated to the better U-value of the cushion. The reflective properties of the silver dotted print on one of the layers of the ETFE cushion also assisted the effect of the insulating properties of the cushion on the maintenance of internal conditions. The lower measured radiant temperatures within the ETFE box under a clear sky can be justified through the transparent nature of the material towards long-wave radiation and the fact that the membrane allowed for heat to escape.

The ability of the IES model to accurately simulate the recorded energy consumption and internal measurements is discussed in the following section.

4.2 IES model accuracy

A linear regression analysis was performed for the measured and simulated energy data for the glass model, resulting to a bivariate correlation coefficient R of 0.98, indicating a strong relation of the dependent variable simulated energy consumption to the independent variable measured

energy consumption. An error of 0.006 kWh resulted for the estimated energy consumption model.

A linear regression was also performed to examine the accuracy of the calculated air and radiant temperatures, in which case the correlation coefficients were 0.99 and 0.99 correspondingly, with an estimated error of $-2.2\text{ }^{\circ}\text{C}$ for the simulated air temperature and $1.5\text{ }^{\circ}\text{C}$ for the simulated radiant temperature. A linear regression analysis was also performed for the ETFE model, resulting to a bivariate correlation coefficient of 0.98 and an error of 0.010 kWh. The correlation coefficients for air and radiant temperature were 0.99 and 0.99 and the estimated errors were $-0.3\text{ }^{\circ}\text{C}$ and $2.1\text{ }^{\circ}\text{C}$ respectively.

The good correlation values suggest that IES was successful in providing an accurate model for the prediction of energy consumption and internal air and radiant temperature.

4.3 Analysis

The measured and simulated results were divided into two groups corresponding to clear sky and overcast sky weather data. The analysis regards only night-time data to avoid the effect of shortwave radiation and the consequent overheating of the boxes. A linear regression was performed to determine the relationship of the measured and the estimated energy consumption for each of these categories. Under a clear sky the correlation for the ETFE box simulation was 0.85 and for the glass box simulation it was 0.84, whereas under an overcast sky the corresponding correlations for ETFE and glass were 0.95 and 0.94 respectively. This indicates the ability of the design tool to calculate energy response more accurately under a cloudy sky rather than under a clear sky.

The level of accuracy of the energy consumption simulations can be considered equal for both materials. As the interest of this paper revolves around the modeling of an ETFE cushion, the analysis will focus on this roof material. Furthermore, since the simulation under an overcast sky presents very high correlation coefficients, the analysis will proceed concentrating on interpreting the simulation inaccuracy under a clear sky in particular.

The measured and simulated energy consumption is expressed relative to the difference between internal and external air temperature (Figure 3).

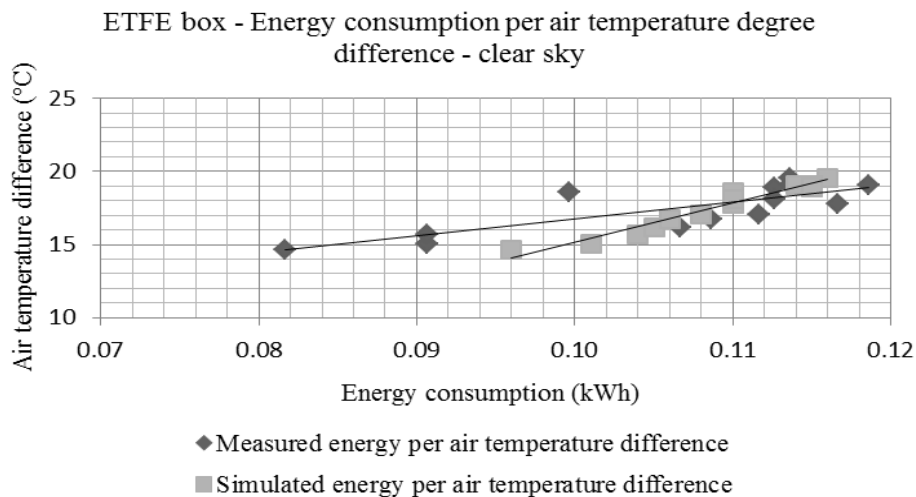


Figure 3. Energy consumption per air temperature degree difference under clear sky conditions.

The points where there was a noted significant deviation between measured and simulated energy per air temperature difference coincided with lower recorded radiant temperatures and the related lower sky emissivity, as well as lower relative humidity levels, which are features associated with a very clear sky. This suggests that the IES model failed to take into consideration the low clear night sky temperature; which would affect the estimation of the amount of heat escaping the box in the absence of clouds and solar input. This fact could be related to the uncer-

tainty accompanying a weather data file, since it only takes into account a certain number of aspects of the sky nature over hourly time intervals.

5 CONCLUSIONS

Ethylene Tetrafluoroethylene (ETFE) membrane is an innovative, sustainable substitute to glazing. The benefits that accompany the use of ETFE cushions include good energy saving potential due to their daylight transmittance, low embodied energy, light weight and thermal behaviour that is comparable to that of an average double glazed unit. Thermal performance data for ETFE, either in the form of a single membrane or a cushion, is not commonly found in material libraries that are employed by energy design programs, leading designers to use glass material properties as the default option. This leads to errors when calculating the energy consumption of a building employing ETFE cushions, which is what this study aimed to amend; particularly in the case of the energy related to space heating. The results of this work should be useful to designers wishing to evaluate ETFE cushions as an option in the attempt to optimise the energy profile of a building and minimise risk and error.

The proprietary thermal modelling tool IES-ve showed good agreement between simulated and experimentally measured energy performance but further work is required to address discrepancies of modeling under different sky types and to ascertain the effect of simplification of the cushion geometry.

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