ENERGY MODELLING OF ETFE MEMBRANES IN BUILDING APPLICATIONS

Harris Poirazis, Mikkel Kragh, and Charlie Hogg
Arup, 13 Fitzroy Street, London W1T 4BQ, United Kingdom

ABSTRACT

ETFE (ethylene tetrafluoroethylene) is a lightweight material increasingly used in building applications. It has gained popularity mainly due to its daylight transmittance and the potential for energy savings. When used as cladding ETFE sheets are usually assembled into cushions, which are inflated for structural reasons. ETFE cushions can provide thermal insulation with reduced initial costs and less structural supports as compared with a conventional glazed roof. Limited research regarding the modelling of ETFE in building applications and limited availability of information on material properties led to the present study. Designers are currently facing difficulties when carrying out energy optimisation studies as part of the design process. For example, since ETFE is not entirely opaque to longwave radiation, merely treating the material as a standard glass layer can lead to errors when evaluating its thermal performance. In order to enable building designers to assess the performance of these systems, maximising performance and managing risk, it is essential to gain knowledge and develop methods to model this novel material. This study takes into account the longwave transmission properties of the ETFE material and discusses the need for a methodology for estimating surface temperatures, heat losses, and solar gains. Guidelines for integration are needed to define its properties and to evaluate performance during the building design process.

INTRODUCTION

ETFE is a relatively new, lightweight material increasingly used in buildings, mainly due to its lightweight properties, its high daylight transmittance and the potentials for energy savings. When used for cladding, sheets of ETFE are usually assembled into cushions which are inflated (for structural reasons) by means of compressors. The system consists of two or more sheets of foil laid on top of each other and joined at the edges to form the cladding equivalent of an inflatable cushion. As stated, ETFE cushions can provide thermal insulation, with reduced initial cost investments and fewer supports compared with a glazed roof (Robinson, 2005). However, due to the lack of information on the material properties it becomes difficult for designers to deliver energy performance optimised designs. Additionally, since ETFE is not opaque to longwave radiation, treating it as a glass layer can lead to errors, when evaluating its performance. Therefore, it becomes essential to gain knowledge and develop methods to model this material in order to maximise performance (and minimise risk).

AIM OF THE STUDY

This paper deals with energy transmission aspects of ETFE in building design. The study focuses on thermal and optical performance of ETFE. Initially, a brief description of the ETFE material is given in order to reach a fundamental understanding of its performance. Calculation methods and approaches for existing projects are mentioned and a first evaluation of these methods is outlined. The paper presents recommendations for further studies of ETFE energy transfer modelling for building performance simulation.

BACKGROUND

ETFE in building design

ETFE has approximately 95% light transmittance, but does not offer the clear visibility/transparency of glass (Robinson, 2005). As a result, ETFE solutions therefore initially found use on projects such as botanical gardens, zoological gardens, swimming pools, and exhibitions spaces. However, ETFE is increasingly finding its place in more traditional buildings as roofing for courtyards, shopping malls, atria and stores. The ETFE material has been used on prominent architectural projects such as the Eden Centre and the Water Cube and it is currently considered for a number of high profile international sports venues. Previous ETFE studies have focused mainly on structural properties and related issues, while little research has been carried out in order to determine energy transmission properties and characteristics in terms of environmental building design.

Figure 1 ETFE in building design

Modelling of ETFE in building simulation tools

Implementing ETFE cushions in building design is a complicated task due to the unusual transmission characteristics of the material. Since currently available commercial software tools are not developed to take into account the longwave transmittance through the ETFE layers, in practice ETFE foils are usually modelled as glazing units. Depending on the building use, the building design, the site, and geographical location of the building, this simplification may impact on the accuracy of the simulated building performance, as discussed in the following.

Shortwave and longwave radiation

This section presents a brief theoretical background, in order to gain an understanding of the particular properties of ETFE and the resulting potential shortcomings of current energy modelling tools and methods.

Electromagnetic radiation is an energy form, which comprises what we refer to as heat and light. The electromagnetic spectrum is outlined in Figure 2. The term 'thermal radiation' (relating to heat transfer) ranges from a wavelength of approximately 0.1µm to 100µm and includes part of the ultraviolet (UV) and all of the visible light and infrared (IR) radiation.

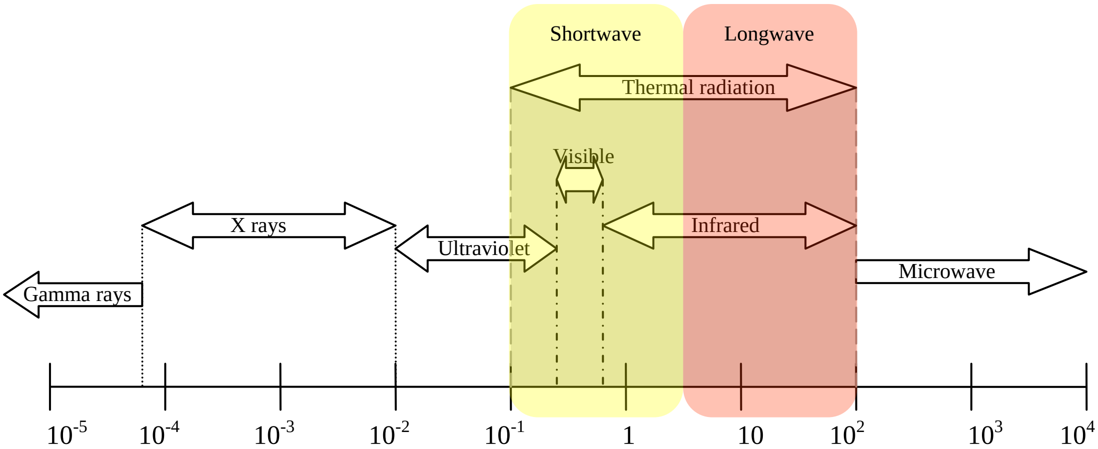

Figure 2 Bands of the electromagnetic radiation spectrum

All bodies emit and absorb energy in the form of electromagnetic radiation. At a given temperature, the thermal radiation emitted from a surface varies for different wavelengths. The term 'spectral' is used to indicate this dependence. The spectral distribution depends on the characteristics and temperature of the emitting surface. In order to accurately quantify radiative heat transfer, the spectral and directional effects should be taken into account (Incropera et al., 2002).

ETFE THERMAL AND OPTICAL PROPERTIES

General

One of the main reasons for using ETFE is the low thermal transmittance achieved for large span modules (Robinson-Gayle et al., 2001). In Table 1 a comparison of thermal transmittance (U-value) and total solar energy transmittance (g-value) of insulating glazing units and ETFE cushions is presented.

Table 1
Thermal and solar transmittance for glazing units and ETFE cushions (Salz et al., 2006)

	U-value (W/m^{2}K)	g-value
6mm monolithic glass	5.9	0.95
6-12-6 Double Glazing Unit (DGU)	2.8	0.83
6-12-6 High Performance Double Glazing Unit (DGU)	2.0	0.35
2 Layer ETFE Cushion	2.9	0.71-0.22 (with frit)
3 Layer ETFE Cushion	1.9	0.71-0.22 (with frit)
4 Layer ETFE Cushion	1.4	0.71-0.22 (with frit)

The thermal and optical properties of the ETFE cushions can be altered significantly by application of coatings, print, geometry and the build-up in which they are applied. The following two examples illustrate how energy transmission through an ETFE cushion (transmission, reflection and absorption) can be modified (Salz et al., 2006).

- Application of a reflective frit to an inflatable intermediate cushion; the intermediate foils can be in an open or closed position allowing heat and daylight into the inner space as shown in Figure 3.

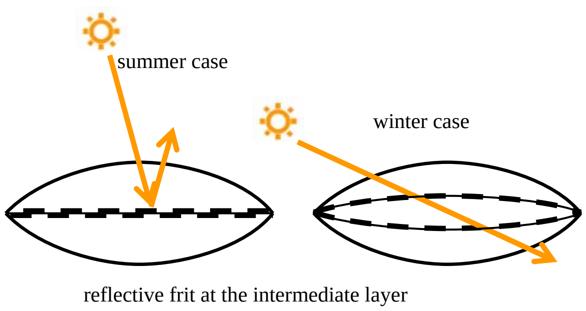

Figure 3 Frit in ETFE cushion

Application of coatings (low emissivity coating in order to reduce the longwave transmission losses i.e. during a cold winter night providing lower thermal transmittance values and/or solar control coating in order to reduce the solar transmittance) as shown in Figure 4.

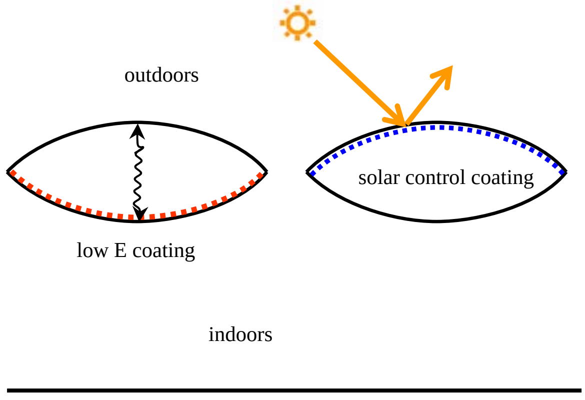

Figure 4 Coatings in ETFE cushion

Usually ETFE cushions incorporate two or three air chambers. Convective heat transfer within these air chambers will influence the thermal performance of the cushion and estimation of U-values is generally complex. Modelling of ETFE cushions as part of building performance simulation is therefore not straightforward. The performance of the systems can be assessed by means of computational fluid dynamics (CFD) and/or by empirical (hot box) testing.

Transmission properties of ETFE and glass

A potentially important difference between glass and ETFE is the way in which longwave radiation is blocked or transmitted. Glazing is virtually opaque to longwave radiation, while ETFE transmits part of the longwave radiation as indicated in Figure 6 (Salz et al., 2006). It is difficult to obtain information on the physical properties of ETFE for the longwave spectrum. Precise knowledge of the ETFE spectral behaviour is essential for increasing the confidence in predictions for the impact of longwave radiation on the building performance. It should be clearly stated that the information in Figure 5 is not confirmed for its accuracy and has been included for illustrative purposes only.

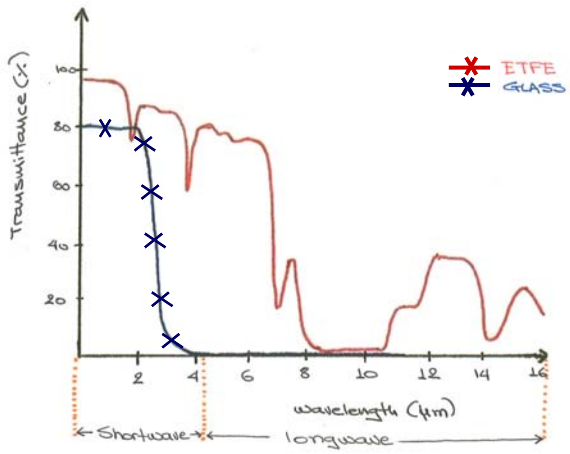

Figure 5 Spectral transmission through Glass and ETFE

The visual light transmittance of ETFE is 94-97% with ultraviolet transmittance being in the 83-88% range. Within the visible part of the solar spectrum the frequencies are fairly evenly transmitted through the material, which means that the colours viewed through the ETFE are not disturbed (Robinson, 2005).

As mentioned above, glass is practically opaque to longwave radiation. For a given glass surface, the longwave radiation emitted depends on the surface emissivity and temperature. A temperature difference between the pane and its surroundings will result in exchange of longwave radiation. In Figure 6 a comparison of the mechanism between a 'triple glazed unit' and a triple-layer ETFE cushion is presented.

- Triple Glazed Unit, exposed to solar radiation:

- Incident solar radiation reaches the 1st pane; part shortwave and part longwave radiation.
- The shortwave radiation is transmitted, absorbed, and reflected. The absorbed energy will lead to an increase in the temperature of the 1st pane. The same applies for the 2nd and 3rd pane.
- The glazing is practically opaque to longwave radiation. In terms of longwave radiation exchange, the relatively very high temperature of the sun means that the exchange is completely dominated by the incident longwave radiation from the sun. However, depending on the temperature difference between the panes and the emissivities of their surfaces, longwave radiation is exchanged between the 1st and 2nd pane similar is the mechanism between the 1st pane and the outdoor environment. Depending on the radiative temperatures of the panes and the surroundings, the net (or resulting) longwave radiation flux can be inwards or outwards.
- The resulting temperature of the panes depends on the longwave radiation exchange, convection between the panes and absorption (including the effect of multiple reflections). The total solar transmittance (g-value) of the triple glazed system is the sum of the shortwave transmitted part, the net longwave radiation emitted from the 3rd pane to the indoor side, and the energy transfer by convection from the 3rd pane to the indoor side.
- By reducing the emissivity of one of the panes (low emissivity coatings), we reduce the longwave radiative exchange and therefore reduce the thermal transmittance of the system. By filling the cavities with Argon or Krypton, we reduce the heat exchange due to convection between the panes, achieving similar results (lower U-values).

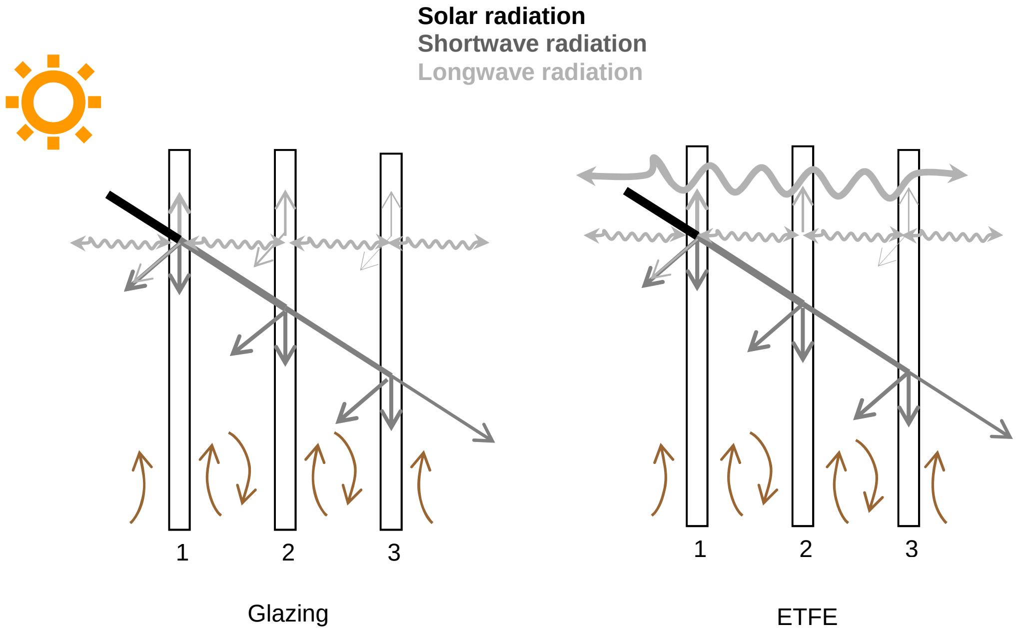

Figure 6 Mechanism of solar radiation for triple glazing and ETFE foils

- ETFE layers, exposed to solar radiation:
  - Incident solar radiation reaches the 1st layer; part shortwave and part longwave radiation
  - As for the glazing system, the shortwave radiation is transmitted absorbed and reflected by the layer. The absorbed shortwave energy leads to an increase in the temperature of the 1st layer. The mechanism is similar for the 2nd and 3rd layer.
  - ETFE is not opaque to longwave radiation. Therefore, when solar radiation reaches the 1st layer, part of the longwave radiation is transmitted. The mechanism of ETFE is similar to the one of glass, but in this case, a reduced part will be absorbed and re-emitted due to the transmission.
  - In the case of ETFE the longwave transmittance impacts on the transmission of energy absorbed in layers (for instance a fritted layer) which is emitted and transmitted through other layers, as well situations where longwave exchange occur between inside and outside across the ETFE. The significance of these effects will vary with the environmental conditions and the properties of the ETFE build-up.

ETFE PERFORMANCE

This study has identified a pronounced need for detailed information and documentation of ETFE material properties. In particular, information on energy transfer characteristics ETFE is scarce. Consequently, a level of uncertainty still surrounds the thermal performance of ETFE.

Effect of long wave transmission on building performance

In order to better understand the potential effect of longwave transmission on the resulting building performance, a space with a glazed roof is compared with a space with an ETFE roof for two scenarios: a cold (winter) night and a warm sunny (summer) day.

During a cold winter night with clear sky the temperature of the floor within the space will be higher than the radiant temperature of the sky. Since the indoor space will be able to transmit longwave radiation through the ETFE roof directly to the cold sky, a longwave exchange between the indoor space and the outdoor environment will take place. The resultant heat transfer depends on the temperature difference, the temperature of the ETFE layers and their longwave transmission properties. Similarly and depending on view factors, longwave radiation exchange may occur between the occupied space and the surrounding buildings.

When exposed to solar radiation, during a warm summer day, the shortwave energy transmission will typically dominate, but longwave radiation exchange will potentially affect the resulting heat transfer, depending again on the temperature differences between the different ETFE layers (which may include fritted and thus absorbing layers) the floor of the occupied space, the sky and any surrounding buildings.

Impact of frit on longwave transmission

A key parameter influencing the performance of ETFE cushions is the possible presence of a fritted intermediate layer (Figure 7). In general, the main purpose of the frit is to introduce shading and reduce the transmitted solar energy into the occupied space. The solar transmission may be variable by means of multiple fritted layers, which can be regulated to vary the combined shading effect.

During a cold night, such a frit would increase the thermal insulation, since its opacity to longwave would reduce the longwave heat transfer between the floor and the sky.

During a warm sunny day, the frit will reduce the amount of shortwave radiation entering the space; the higher the frit density, the lower the direct shortwave penetration. The frit will reflect a part of the shortwave and absorb another part increasing the temperature of the layer. A highly absorbing frit would increase the temperature of the middle layer more than a highly reflecting one, increasing the emitted longwave radiance (towards indoors and outdoors depending on the temperature differences and emissivities). On the other hand, since the frit is opaque to longwave radiation, a fritted intermediate layer would shield from transmission of longwave radiation from outdoors.

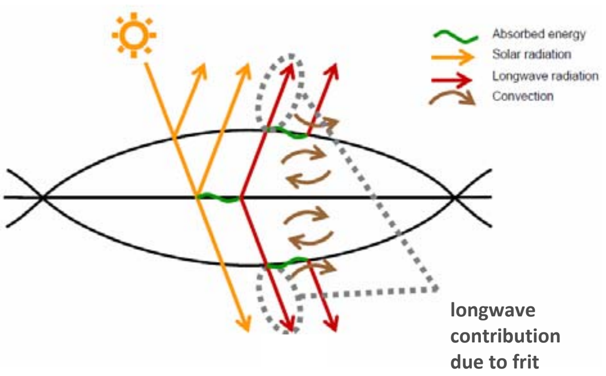

Figure 7 Impact of fritting on ETFE performance

The impact of fritting reduces the risk of overheating of a space, but the energy transfer mechanism is complicated.

Quantifying the impact of an longwave transmission through an ETFE roof; a case study

Accurate assessment of ETFE systems and their impact on building energy performance (including thermal comfort) is currently not possible due to (a) uncertainty regarding longwave physical properties of ETFE and (b) dynamic building performance simulation software tools do not take into account the spectral properties of ETFE in the underlying calculation methods.

However, in order to assess the effect of longwave transmission and investigate whether the current practice of modelling the ETFE as glass significantly impacts on the simulated building performance, a preliminary study was carried out for a summer scenario. The study was divided in three parts:

- Comparison of the relative effect of heat transfer by convection and longwave radiation
- Estimation of expected maximum ETFE layer temperatures
- Development of a simplified mathematical model based on heat transfer balance for each layer

The simplified mathematical model was developed in order to estimate the effect of longwave radiative transmission through an ETFE cushion. The study was carried during the early design stage of a stadium project. The main objective was to evaluate whether the longwave contribution affects substantially the simulated building performance and therefore, whether, consequently, it should be included in the dynamic thermal model. The ETFE cushions were modelled as a roof and the calculations were carried out for the project design summer conditions.

The heat flow model for the ETFE cushion was developed by taking into consideration the heat balance for each of the component ETFE layers. For each of the layers the radiative and convective heat transfer were included in the heat balance (including the transmitted radiation). The main output of the developed model were the ETFE layer temperatures and the roof element heat fluxes. This output is purely indicative and serves to assess the impact of longwave radiative transmission properties on the resulting thermal performance of the element.

The assumptions and constraints incorporated into the simplified model are described below:

- The model deals with a single roof element; therefore, wall effects are not included.
- Linear radiation heat transfer coefficients were assumed. The same coefficients were used for all layers of the cushions irrespectively of their temperature. This potentially leads to underestimation of emission from hot surfaces and overestimation of radiation from cold surfaces.
- The air temperature within the cushion is taken as the mean temperature of the two adjacent layers.
- The sky radiation temperature and the outdoor dry bulb temperature are assumed the same (humid conditions).
- The indoor mean radiant temperature is assumed identical to the indoor dry bulb temperature.
- The layers have a longwave reflectivity of 0 and a longwave emissivity of 1.

- The amount of incoming solar radiation absorbed by the ETFE layers is assigned explicitly to each layer (see Figure 8).
- The ETFE layers in the build-up all have the same transmittance. The ETFE longwave transmittance was arbitrarily set to 0.2 (while the corresponding transmittance of glass is 0.0)
- This approach does not account for any longwave absorption of interlayer shading. The effect of the intermediate layer frit on the longwave transmission was not accounted for.

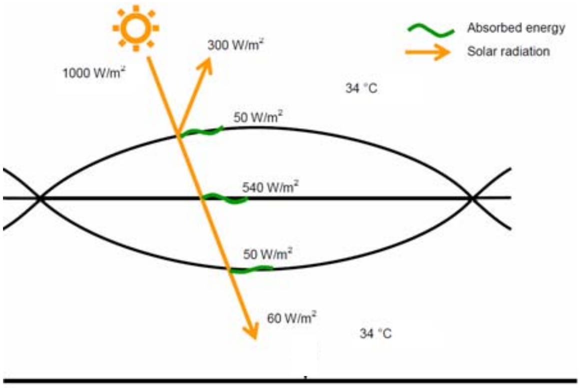

Figure 8 Boundary conditions for mathematical model of the roof (longwave radiative convective heat transfer evaluated by the model are not shown)

For comparison the performance of glass and ETFE systems have been calculated for particular environmental conditions, chosen to represent a roof solution with a fritted interlayer in a hot humid climate.

Table 2 presents the heat fluxes to the internal environment and the temperatures of each layer within the glazing and ETFE system given by the simplified model.

Table 2 Heat fluxes and temperatures for a simplified glass and ETFE model (for both cases direct solar transmittance (T_{dir}) of 6% was assumed)

	GLASS	ETFE
Longwave radiative gain [W/m^2]	195	218
Convective gain [W/m^2]	73	56
Total gain [W/m^2]	328	334
External layer temperature [°C]	48	45
Interlayer temperature [°C]	81	74
Internal layer temperature [°C]	58	53

The main conclusions drawn from this study are:

- The ETFE construction has a 12% increase in the longwave heat flux from the element when compared to a glass construction.
- The ETFE construction has a 2% increase in the total heat gain through the element.
- In a scenario with solar radiation, the effects of longwave transmission through the ETFE are not considered significant (especially when considering the errors that may occur by inaccurate input in the thermal models).
- For other configurations and different environmental conditions, the longwave transmission is likely to have a more significant impact on the simulated thermal performance of ETFE building elements. A particular condition where the simulated performance of ETFE may be significantly different to that of glazed systems is that of radiation from the indoor side to a cold sky at night. The magnitude of this impact has not yet been specifically investigated but will be the subject of further research and simulation activities.

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

The main aim of the present study was to describe the state-of-the-art regarding the understanding of ETFE energy transfer characteristics and performance assessment methods. Further research is suggested with a view to evaluating in more detail the performance of ETFE and increase confidence in its implementation during the design process.

ETFE properties

Available information on ETFE spectral properties is scarce. Previous studies in this field are limited and manufacturers appear to treat the information as confidential. As a first step, accurate and validated data on ETFE spectral properties (transmittance, absorptance, reflectance) have to be gathered. The information shown indicatively in Figure 6 above should be verified.

In the absence of verified manufacturers data, it may be necessary to collect representative samples and carry out certified measurements in collaboration with relevant research centres.

Assessing the impact of longwave transmission

Previously, efforts have been made to evaluate the impact of longwave transmission on total heat transfer. The mathematical model developed as part of the present study was highly simplified and focusing on the maximum potential effect during a warm summer day. According to the results obtained from this tool, the impact of longwave transmission is insignificant for a warm sunny day. The impact in a 'cold night' scenario should be investigated, but the present model is not suited due to the specific simplifying assumptions introduced. Tentative models did not provide confidence in the applicability of the tool for the different boundary conditions and further work is required.

The assumptions made were entirely reasonable for the specific study, but before the tool is applied to other cases consideration should be given to the following:

- Error due to linearised radiative heat transfer coefficients.
- Inclusion of longwave opacity of the frit.
- Individual layers modelled separately in terms of transmittance, reflectance, and emissivity.
- The model should be further validated.

A tool that can assess the longwave transmission effects for steady state boundary conditions would be essential in order to assess its impact and evaluate whether necessary to implement the spectral transmission model concept in a dynamic building performance simulation tool.

Implementation of longwave transmittance model in building performance simulation tools

Currently, there is no dynamic building performance simulation tool that incorporates spectral properties of layers in the 'window' model. In most of the cases an average transmittance, reflectance and absorptance are defined for the shortwave region and reflectance and absorptance are defined for the longwave part of the spectrum. The emissivity of the different layers is also defined as constant values. For conventional glazing these assumptions are acceptable, since the transmittance of panes is relatively constant across the shortwave range. However, the following questions arise:

- How is reflectance and absorptance treated across the longwave part of the spectrum?
- Is it reasonable to assume an average transmittance across the whole spectrum for ETFE materials? Since the magnitude of radiation at any wavelength varies with the characteristics and temperature of the emitting surface, the amount of estimated transmitted energy from/through an ETFE layer may depend on the assumed spectral properties.
- Similarly, is it reasonable to assume an average emissivity for all wavelengths for an ETFE material?

To sum up, it would be relevant to investigate how various available building performance simulation tools treat longwave radiation and (depending on the results of the research proposed above) consider further development of tools either for generic use or specifically for the purpose of assessment of longwave transmission effects.

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