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BUILDING PHYSICS OF ETFE-FOIL SYSTEMS

M. KERSKEN*, A. KAUFMANN*, K. MORITZ, W. KRAH[ж], F. GOECKE[†]**

* Fraunhofer Institut for Building Physics IBP, Fraunhoferstrasse 10, 83626 Valley/Oberlaindern, Germany,
e-mail: matthias.kersken@ibp.fraunhofer.de, web page: https://www.ibp.fraunhofer.de

** Taiyo Europe GmbH, Mühlweg 2, 82054 Sauerlach, Germany,
e-mail: k.moritz@taiyo-europe.com, web page: https://taiyo-europe.com/de/

ж Dr. Krah & Partner - Partnerschaft von Sachverständigen und beratendem Ingenieur mbB, Mittelstrasse 5, 96163 Gundelsheim, Germany,
e-mail: svkrah@krah-partner.de, web page: https://krah-partner.de/

† se-cover GmbH, Bahnhofstrasse 28, 83119 Obing, Germany,
e-mail: florian.goecke@se-cover.com, web page: https://seele.com/de/

Key words: U-value, ETFE foil cushion, IR-transparency, emissivity, heat flow direction, cushion inclination.

Summary. This paper introduces into the building physic principles, discusses the applicability of existing standards on the U_g-value calculation and introduces a method to consider the IR transparancy of ETFE foils.

1 INTRODUCTION

This paper presents the principle influences on the heat transport mechanisms in ETFE foil systems and elaborates on differences in heat transfer coefficients that were determined using different calculation methods (standards) and different boundary conditions.

Transparent and translucent ETFE foils have been used as a component in architecture since the early 1980’s. As single-layer structure and as multiple layers air inflated structure, applied in roofs, façades or as a whole building envelope, they have a significant influence on the energy demand and the comfort of the enclosed space.

ETFE foil systems used as building envelope have to meet requirements for winter and summer heat protection as well as moisture protection. It is therefore important to know the building physical properties of the foil systems and the influencing factors. Depending on the number and spacing of the individual foil layers and the installation situation (horizontal, vertical, inclined), the proportions of heat conduction, heat radiation and convection in these systems change. The foil layers are usually double-curved, are neither parallel to one another, nor are all surfaces perpendicular to the solar radiation at the same time. The building physics of such systems is very complex, therefore. In the absence of a material-specific standard, the currently available standards are inevitably used to determine building physical parameters such as U_g-value and g-value. Since such systems are transparent or translucent, the standards usually applied are primarily related to glass or windows. It should be noted, however, that ETFE foils (depending on the intensity of their printing) are more permeable to radiation in the infrared spectrum than glass. This is an essential difference, since glasses are almost opaque in this spectrum (5 – 50 µm). It means that the applicability of certain existing standards has not been validated so far. In that sense it is an open question if they can be used or if adaptions are required. This applies in particular to the determination of the standardized heat transfer coefficient (U_g-value [W/(m²K)]) which is used to compare different building elements.

2 BUILDING-PHYSICAL BASICS

Basically, the question arises as to how the building physics parameters can be predicted for a lightweight single-chamber or multi-chamber construction with transparent or translucent foils. This applies in particular to the parameters U_g-value (U_g as the heat transfer coefficient of the transparent cushion area; comparable to the glazed area of a window or façade), g-value and temperature gradients. The temperatures are relevant for the estimation of dew point undershoots and the risk of condensation.

In the past, statistical models were often applied and empirically verified. Today, computer-based computational programs and CFD methods allow simulation of the multidimensional processes of heat conduction, radiation, and convection. The basics are briefly presented in the following.

2.1 Conduction

Heat conduction deals with the calculation of the heat flow through a solid. If we consider a typical multi-chamber system made of foils, in terms of heat conduction it consists only of the foils and the clamping profiles. The thermal resistance of the thin foils can be neglected, while the heat transport through the air chamber is determined by convection. On the other hand, the thermal resistance of the clamping profile is not negligible. However, the heat conduction through the profile can be calculated by means of two-dimensional heat flow calculations with suitable software. The heat flow in corners, intersections and T-joints can also be calculated in three dimensions. Conventional clamping profiles made of aluminum achieve U_f-values between about 4 and 7 W/(m²K), depending on the structure (gaskets and cavity), provided that no additional thermal insulation layers are integrated.

2.2 Radiation

The foils used in single-chamber or multi-chamber constructions, mostly ETFE foils, can be colored or printed. This means that the respective colored or printed foils can be produced between transparent to almost opaque - with corresponding effects on the solar and long-wave, thermal radiation properties of the individual foil layers and thus on the achievable g-value and - to a limited extent - also on the U_g-value of the entire foil system.

In addition, the radiation properties are wavelength-dependent. In addition, the solar radiation components (transmission, reflection and absorption) depend on the angle of incidence on the surface of the respective foil layer, i.e. on the installation angle of the ETFE foil system. Also, solar irradiance is also not constantly distributed over the wavelength spectrum, depending on the altitude of the sun or the path of the radiation through the atmosphere. Since this paper focuses on the U_g-value, i.e., the thermally driven heat transmission through the component, the properties of the solar radiation spectrum will not be discussed further at this point. Instead, properties and characteristics of the long-wavelength, thermal IR spectrum will be presented, since this mechanism of heat transport plays an essential role in the calculation of U_g-values (especially of ETFE-foil systems).

In the thermal range of electromagnetic radiation, at wavelengths longer than 2500 nm, all objects (foils, environment and the near atmosphere) emit in a radiation spectrum that is usually in the range of Planck's 300 K curve for terrestrial applications. All objects are thus in a (thermal) radiation exchange with each other. The intensity of an object’s thermal emission is determined by its temperature and the emissivity of the respective surface. This emissivity is equal to the thermal absorption and corresponds to the fraction that is neither reflected nor transmitted through the material $\varepsilon = \alpha = 1 - \rho - \tau$. For the calculation of this radiation exchange between the individual layers of the foil systems, suitable standardized measurements of the transmission and the reflection in the wavelength range up to 50 µm are required in order to be able to calculate the emissivity of the foils used. It should be noted here that contamination and aging processes in materials can fundamentally change the spectral properties. However, rain cleans the surface of ETFE foils (depending on the installation situation), and notable discoloration or an increase of hazing of ETFE foils has not yet been observed, even after many years of weather exposure.

ETFE foils show a significant difference to the glass used in architecture. While glass is almost opaque in the infrared range (IR), the transparent ETFE foils have a significantly higher transmission in this spectral range. The transmission - also in the IR spectrum - can be influenced by printing the ETFE foils. As higher the degree of printing is selected, the lower are the transmission and the higher are the reflection/absorptions also in the IR spectrum. Figure 2.1 till Figure 2.3 show the longwave spectral properties of three differently printed ETFE foils, unprinted to almost completely printed, in comparison with an uncoated 4 mm float glass. Here it is clear that transparent ETFE, unlike glass, exhibits strong transparency, up to 20 % in the IR range. This transparency is reduced close to the level of glass as the degree of printing increases.

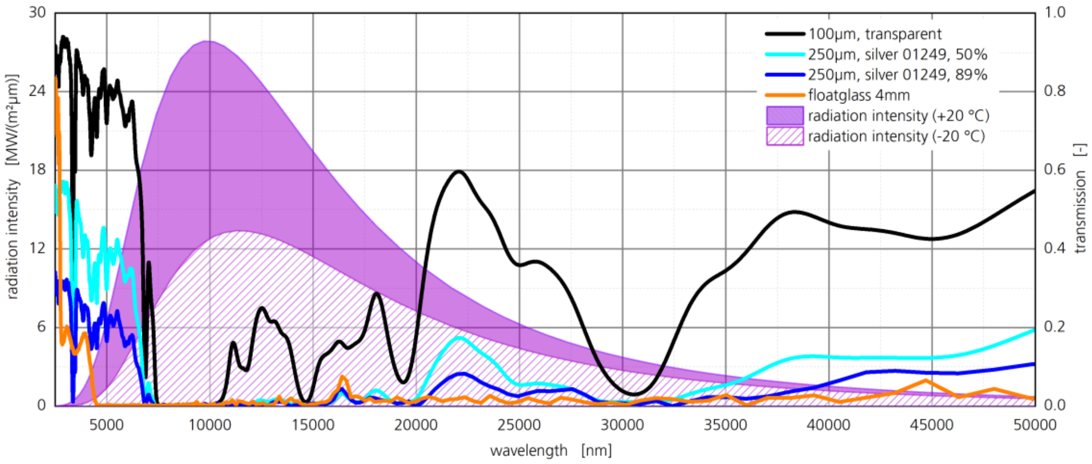

Figure 2.1: Spectral distribution of IR transparencies together with Plank's black body distribution.

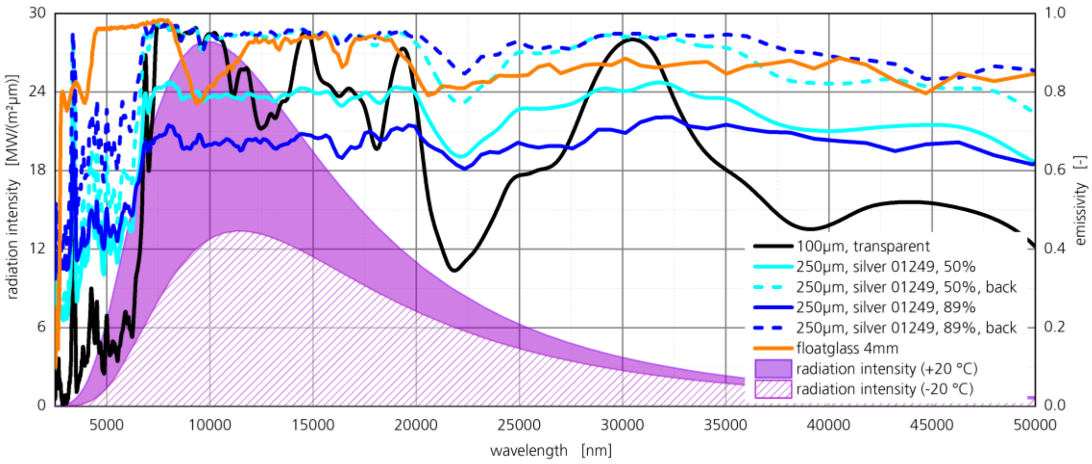

Figure 2.2: Spectral distribution of IR emissivities together with Plank's black body distribution.

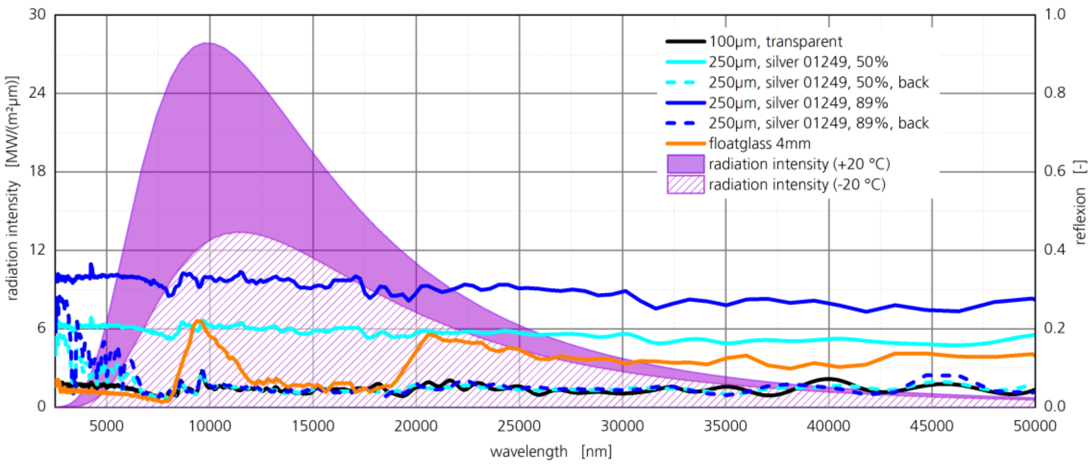

Figure 2.3: Spectral distribution of IR reflectivities together with Plank's black body distribution.

2.3 Convection

Pneumatically supported single-chamber and multi-chamber systems have, system-dependent, single- or double-curved surfaces, which enclose a considerable volume of air. The volume [m³] enclosed between the foil layers is about 40 – 60 % of the projected surface [m²] of the cushion, depending on the sag or geometry. Therefore, convection basically represents a non-negligible portion of the three heat transport mechanisms.

Regarding convection, the installation conditions play a decisive role. A distinction is therefore made between horizontal heat flow (90°, vertical façade) and vertical heat flow (0°, roof). Other angles of inclination (e.g. 45°) are possible. In addition, depending on the temperature gradient considered, the heat flux can be directed from the inside to the outside (winter, cold regions, heating capacity) or from the outside to the inside (summer, hot regions, cooling capacity).

The U_g-value is therefore significantly influenced by the two parameters angle of inclination and direction of heat flow, as shown by thermal CFD flow simulations by Antretter[1] on a foil cushion cross-section and various installation situations (Figure 2.4 till Figure 2.6).

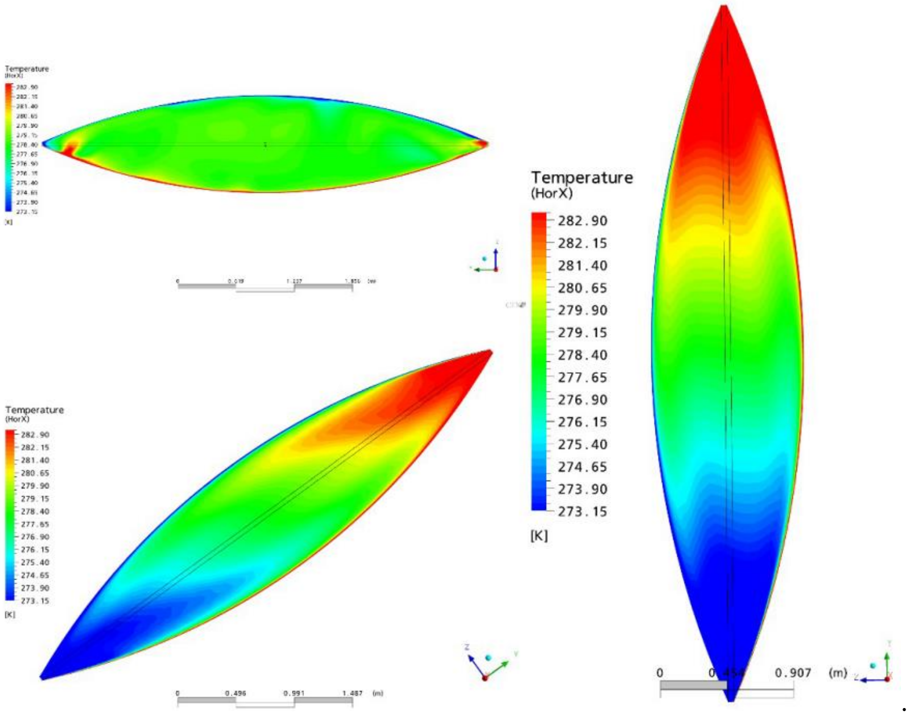

Figure 2.4: One-chamber-cushion, different assembly situations (heat flow directions) - temperature distributions for 20°C inside and -10°C outside[1].

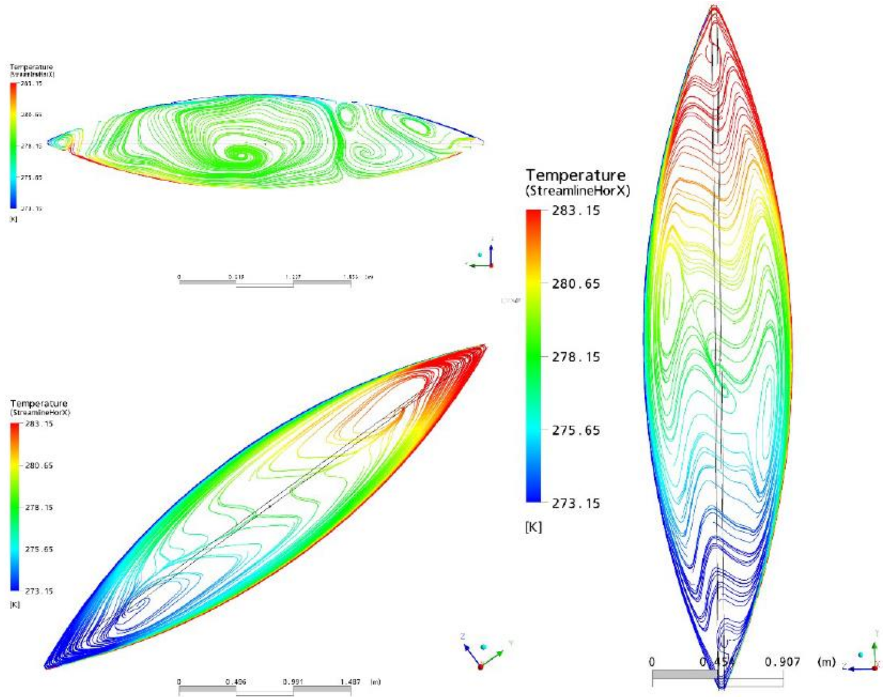

Figure 2.5: One-chamber-cushion, different assembly situations (heat flow directions) - temperature at the air currents for 20°C inside and -10°C outside[1].

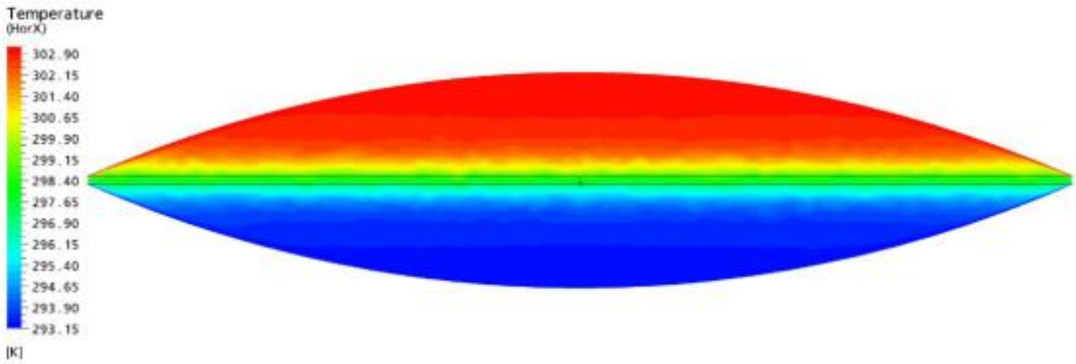

Figure 2.6: One-chamber-cushion, vertical heat flow (downward) - temperature distribution for 20°C inside and 30°C outside[1].

The horizontal single-chamber cushion with upward heat flow (cold at the top, warm at the bottom, Figure 2.4 and Figure 2.5) shows an almost constant temperature over almost the entire cushion height. Only near the boundary surfaces of the system a strong temperature gradient is visible. This suggests chaotic turbulent flows in the cushion volume. If the direction of the heat flow is reversed (warm at the top, cold at the bottom), the result is a pronounced temperature stratification (Figure 2.6). This is a stable state with little flow, resulting in a significantly lower heat transfer.

On the other hand, the vertical and inclined single-chamber cushions with sideways or upward heat flow (left cold, right warm) result in almost horizontal temperature stratifications (top warm, bottom cold), which promote convection in the enclosed air volume and ultimately lead to a higher calculated heat flow.

With the exception of the horizontal single-chamber system with downward heat flow (Figure 2.6), the variants shown (Figure 2.4 and Figure 2.5) are systems with chaotic flows. Statistical values such as pressure and temperature cannot be easily calculated from the motion curves of individual gas molecules. In other words, even small changes in the system or its boundaries can lead to significant changes in the vortices and thus in the results. For convection, this means that only by performing a statistically sufficient number of simulations or measurements with slightly varying system and boundary conditions can one obtain a sufficient number of results to allow the specification of occurrence probabilities of certain heat fluxes within the cushion system.

The examples clearly show that both the installation situation (inclination) and the direction of the heat flow have a considerable influence on convection and thus on the U_g-value of such systems. While the processes of heat conduction and radiation of single- and multi-chamber systems made of ETFE foils can be simulated or calculated with sufficient accuracy today, the results of simulations of convection are subject to uncertainties. The standardized calculation methods described in section 5.1 use empirical approximations for convection. The extent to which these approximations can be applied to foil cushions is discussed in the following sections 4 and 5.

3 SPECIAL FEATURES OF ETFE-FOIL SYSTEMS

3.1 Differences to Glass in the IR-Spectrum

Have you ever wondered why the U_g-values of ETFE foil constructions from different users can be so different - and this despite identical applied standard (EN 673[2]) and identical constructions (number of foil layers, printing, foil thicknesses, gas gaps, etc.)? The answer is simple. The reason lies in an inadmissible interpretation of the EN 673 standard.

The U_g-value calculation is based on measurements of the spectral properties of the individual ETFE foils including their printing. The measurements of the wavelength-dependent reflectance and transmittance are carried out by accredited testing laboratories in accordance with the relevant standards (DIN EN 410[12], DIN EN 12898[4]). From the measured values of the reflection and transmission, the absorption, in the infrared spectrum the emission, which is also dependent on the wavelength, is calculated according to equation (1) shown below[3]:

$$1 = \tau + \rho + \varepsilon \tag{1}$$

The equation states in simplified form that the total radiation in the IR range is made up of the components of transmission (τ), reflection (ρ) and emission (ε). While the types of glass used in architecture are approximately opaque in the infrared range, transparent ETFE foils allow some of the infrared radiation to pass through. This fact was not common knowledge for a long time, until a few years ago when ETFE foils were examined by spectrograph in the infrared spectrum as well. Since the difference between the two materials are known, laboratory measurements on ETFE foils are now standardly examined not only in the wavelength range between about 300 and 780 nm (UV spectrum) and 780 and 2500 nm (visible light), but also in the infrared spectrum (IR), more precisely between 2500 and 50 000 nm.

The influence of infrared radiation on the heat transfer coefficient (U_g-value) of a multilayer ETFE foil system can be significant. Thus, the printing of one or more ETFE foils of a single-chamber or multi-chamber system has a significant influence too, on the U_g-value. With the aid of the three radiation components τ, ρ and α (absorption) or ε in the infrared range, the U_g-value can be determined according to defined calculation procedures. The available calculation methods are regulated by standards so that different materials and systems can be compared with each other. There is currently no material-specific standard for ETFE foil cushions. Therefore, design teams currently have to work with the building physics standards that exist, especially from window construction.

The EN 673 standard, which is widely used and generally accepted, is used to determine the U_g-value of single and multi-layer glass panes. However, as the name suggests, this standard refers to glazing. As explained in section 2.2 of the standard, glass is almost impermeable to infrared radiation. Therefore, according to this standard, with reference to EN 12898, one may use the following equation (2) to determine the U_g-value:

$$1 = \rho + \varepsilon \tag{2}$$

In contrast to equation (1), equation (2) does not contain a transmission component T. The neglect of transmission in the infrared spectrum (IR) is, of course, only allowed for materials that are completely or at least nearly opaque in this radiation range, such as glass. The application of equation (2) to materials that are transparent in the infrared spectrum (IR), such as transparent ETFE foil, is not permitted according to the scope defined in the standard. The reason for this is that any transmittance would be added to the emissivity, which would seem to reduce the heat transfer.

3.2 Special Features of ETFE-Foil Systems

Air-filled single- and multi-chamber systems made of ETFE foils have other properties that distinguish them from other construction methods and materials. These include, for example, the spatially curved and often inclined surfaces, resulting in varying distances between the foil layers, as does the thickness of the enclosed air layers. Also, the expansions and relatively large deformations of the foils that occur in reality are not taken into account in the proportions of radiation and convection that vary as a result. An U_g-value determined in accordance with the standard can therefore only be a comparative value, but not a value that reflects reality in all situations. Finally, the air exchange rates necessary to prevent condensation in ETFE foil cushion must also be addressed. The air exchange rate of the volumes is typically 1 till 2 times per day, depending on environmental conditions and the use of the building. The air exchange rate can be increased for buildings with high indoor humidity, such as swimming pools, tropical halls, etc. Such air exchange rates and the flow velocities associated with the low air exchange rate, as well as the heat introduced into the system by the drying of the injected air, can usually be neglected when calculating the three heat transfer processes (conduction, radiation and convection).

3.3 Boundary (Clamping Profile)

Single-chamber and multi-chamber systems made of ETFE foils usually consist of a transparent or translucent area (foil cushion) and an opaque frame (clamping profile). The foil cushion usually occupies about 95 % of the projected surface of the overall system (roof, façade), and the frame only about 5 %. It is therefore obvious that a reduction in the U_f-value of the frame has only a minor effect on the U_w-value of the overall system. The goal of a thermal break or an improvement of the thermal insulation properties of the clamping profiles is therefore primarily to avoid condensation rather than to improve the U_w-value.

The U_f-value and the condensation risk of the profiles are determined in accordance with the relevant standards for opaque components in building construction, in particular from the field of window technology (EN ISO 10077-2[5], DIN 4108-3[6], see Figure 3.1).

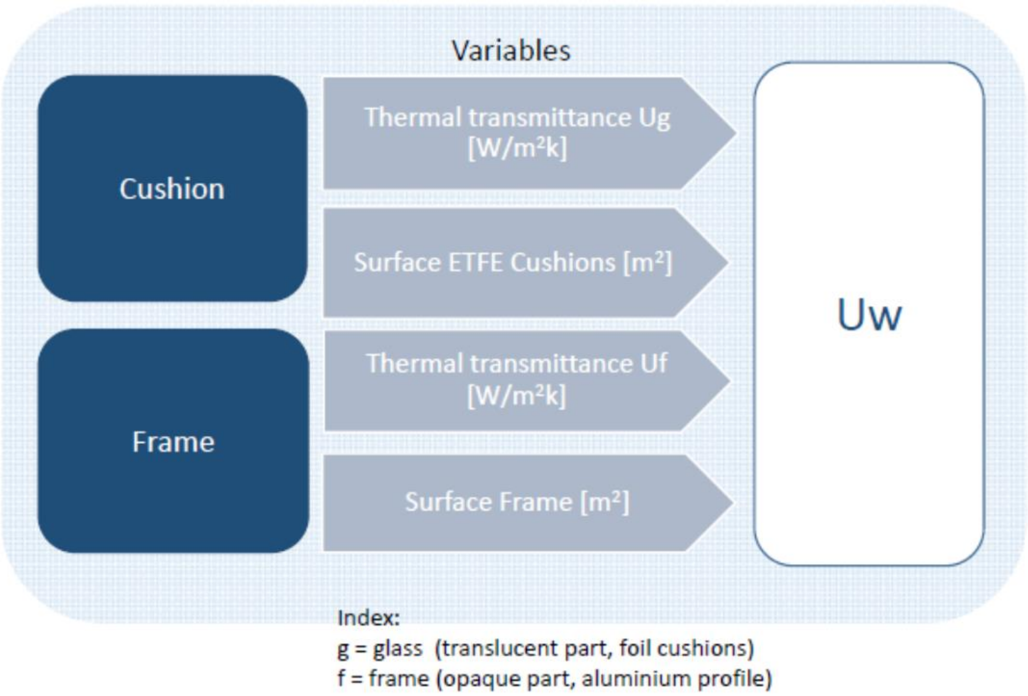

Figure 3.1: Principle work flow of the calculation of U_g-, U_f- and U_w-values, TAIYO EUROPE GmbH[7]

4 MEASUREMENTS

To create validation data for the calculations under consideration, especially for the influence of the specimens' slope on the U_g- and g-values, six different pneumatically stabilized ETFE cushions with different printings, air layer geometries and 3 and 4 foil layers are investigated in the Calorimetric Façade and Rooftop Test Facility[8] of the Fraunhofer Institute for Building Physics IBP. This facility's primary task is the determination of g-values, SHGC and other solar properties. These solar investigations on the ETFE-cushions are not part of this paper and can be found in[9].

Figure 4.1 shows the test facility with the "MEM1" specimen installed. The schematic drawings of the selected two specimens that are discussed in section 5 are shown in section 4. Since in case of solar measurements, the facilities main task, the resulting energy flows are about fifty times higher than during a nightly U_g-value measurement, the calorimetric instrumentation's accuracy is not suitable for this task. To perform the night measurements an alternative setup according to ISO 9869[10], consisting of surface temperature sensors on the inside and outside foil and a heat flux tile on the inside. In this chosen setup the facility's test chamber is used only to provide a stable, homogenous warm side climate without thermal stratification and a specific, well know air speed. To avoid problems with the cushions' curved geometry a flexible, silicon based heat flux tile was used. This tiles thermal resistance is relatively high compared to the 250 μm thick ETFE foil, so a 2D finite element calculation (Flixo-software) is used to compensate for the sensor's influence on the measured heat flow through it.

Figure 4.1: Calorimetric Façade and Rooftop Test Facility with the "MEM1" specimen.

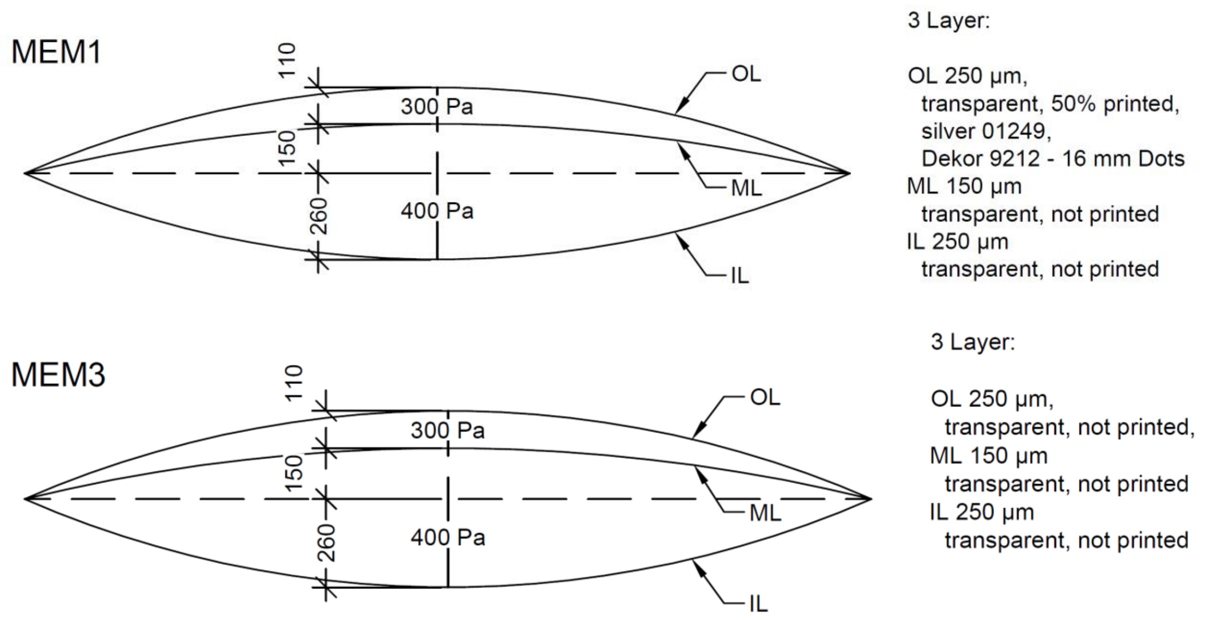

Figure 4.2: Construction of the two selected specimens MEM1 and MEM3.

The application of the heat flux tile method relies on the assumption that the specimen is homogenous enough so the measured local values are representative for the average surface area. Figure 4.3 (left) shows a very homogenous temperature profile over the specimen's height. The apparent temperature increase of about 0.5 K towards the cushions bottom is caused by the thermal reflection of the surroundings with the ground being warmer than the sky. This is no contradiction to the cushion's temperature profile shown in Figure 2.4 because a small layer of cold air stretches along the exterior surface up until the top of the cushion, as can be seen in the detail in Figure 4.3 (right).

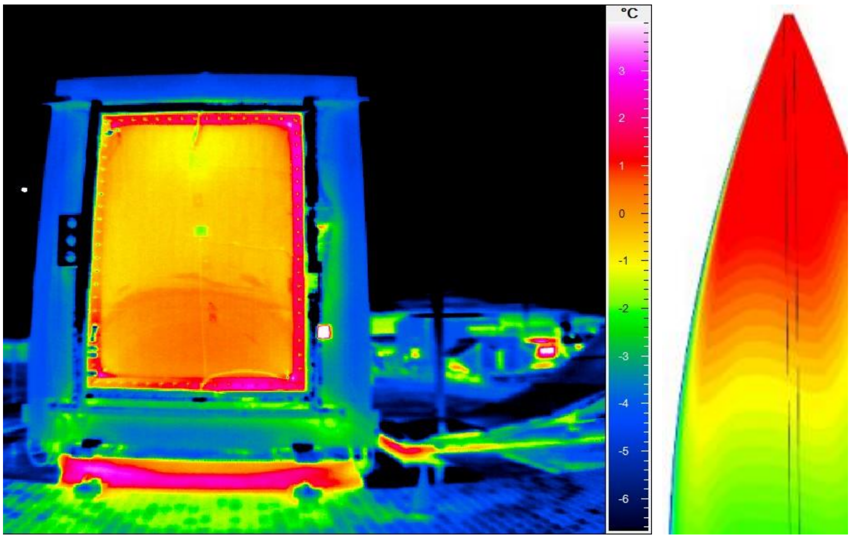

Figure 4.3: Left: Thermal image of the vertical specimen during a night measurement.
Right: Zoom-in detail on the calculated temperature distribution on the vertical cushion (rotated 90° clockwise).

From the heat flux and the temperature difference between both surfaces the specimen's thermal resistance is calculated. On this resistance the standard heat transfer coefficients are imposed. The following equation is used to determine the measured U_g-value. When interpreting the measured U_g-values in Figure 4.4 it must be considered that the heat flux tile is IR-opaque. As a consequence the inner foil, usually quite IR-transparent (unprinted), has changed long wave properties because of the sensor.

$$U_{meas} = \frac{1}{R_{si} + R_{se} + \frac{(\theta_{si} - \theta_{se})}{\dot{q}}} \qquad (3)$$

U_{meas}	: U_g-value determined in the measurement	[W/(m²K)]
R_{si}	: Heat transfer resistance on the internal surface: 0.13 (m²K)/W	[(m²K)/W]
R_{se}	: Heat transfer resistance on the external surface: 0.04 (m²K)/W	[(m²K)/W]
θ_{si}	: Temperature of internal surface	[°C]
θ_{se}	: Temperature of external surface	[°C]
$\dot{q}$	: Heat flow density	[W/m²]

The temperature sensors used are specified with a minimum accuracy of 0.1 K, the heat flux sensor with 5 %. These uncertainties are used to estimate the uncertainty of the U_{meas} by the means of the Monte-Carlo method[11] to ±0.102 W/(m²K) on standard deviation level. Despite these constraints the measurements shown in Figure 4.4 are still suitable to prove the general suitability of the ISO 6946 for membrane cushions.

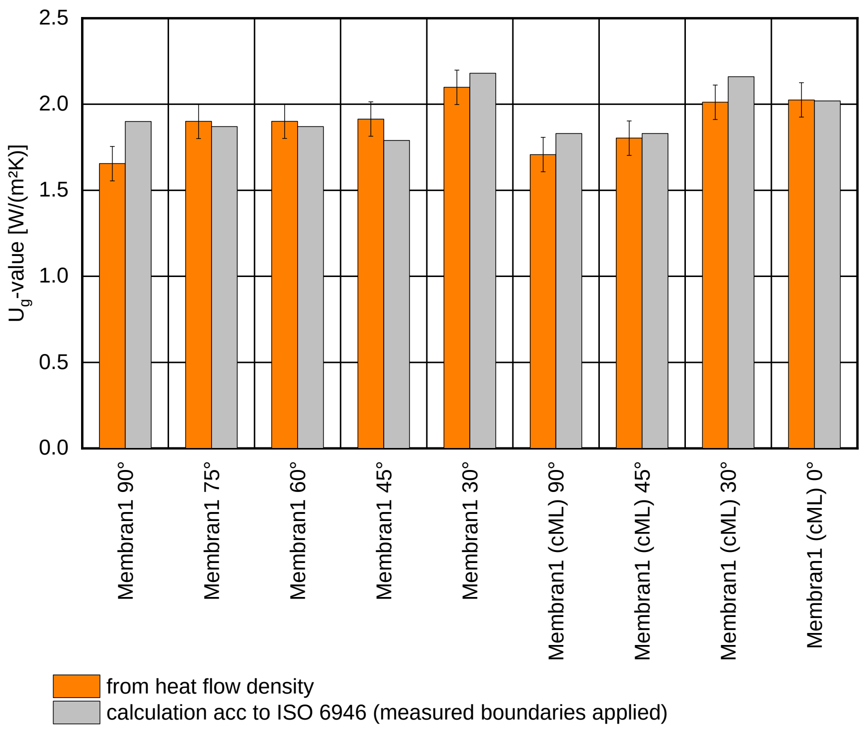

Figure 4.4: Measured U_g-values of the "MEM1" specimen's and according to ISO 6496[10] (cML = changed mid layer). IR-transparency unconsidered. The measurement uncertainty is show on standard deviation level.

5 CALCULATION METHODS (U_g-VALUES)

5.1 Calculation Methods according to the codes

Different codes (standards) can be applied to calculate the U_g-value. The respective guidelines refer to different boundary conditions and material parameters. Depending on the standard under consideration, boundary conditions, material parameters and whether transmission in the IR range is taken into account, the U_g-values may differ significantly.

EN ISO 6946[12] provides a simple method for calculating the thermal transmittance. However, the scope excludes glazed units and thermal IR transmission is not taken into account. If the standard is applied on ETFE cushions, the calculation according to Annex D of the standard must be extended by a procedure as the one described in section 5.2. Convection is taken into account via the air layer thickness and the temperature difference.

The calculation according to EN ISO 6946 and EN 673[2] are quite similar. A manual calculation is possible with both standards. However, EN 673 refers to glass panes and seems at first glance to be more suitable than a standard for opaque components. However, it excludes an application for layers that are transparent in the far infrared range. Therefore, this standard should also be extended to include the procedure described in section 5.2. In addition, flat and plane-parallel surfaces are assumed. When considering convective heat flow, significantly more parameters can be taken into account than according to EN ISO 6946. Different inclinations can be taken into account in both standards.

ISO 15099[4] offers a much more complex method, taking thermal transmission into account. A large number of parameters can be included when determining the convective heat flow. However, due to the complexity, a manual calculation is only possible with difficulty here.

5.2 Consideration of the IR-Transmittance (ISO 6946, EN 673)

As part of a research project funded by the German BBSR (FKZ SWD-10.08.18.7-15.04), the Fraunhofer-Institute for Building Physics IBP investigated, among other things, the extent to which membrane cushion constructions can be assessed on the basis of available standards and whether there are any limitations to this. ISO 6946 was used as a calculation basis and compared with measurement results at the calorimetric façade and roof test facility of the Fraunhofer IBP at Holzkirchen.

The result of these investigation, described in section 5.4 is, that the calculation method according to ISO 6946, which is based on a thermal resistance model, represents the real measured situation sufficiently to be applied to membrane cushion designs. However, since ETFE also exhibits a certain transparency in the infrared range, this radiative heat transfer component must also be taken into account in the energetic behavior. Since the scope of ISO 6946 is limited only to opaque components and the scope of EN 673 is limited to materials that are opaque in the far infrared range, the thermal transmission of ETFE foil must also be taken into account by some kind of appendix method. EN 673 and ISO 6946 are limited to Kirchhoff's radiation law for opaque components $\varepsilon = 1 - \rho$. To take into account the transmitted radiation component for membrane cushions, $\varepsilon = 1 - \rho - \tau$ applies here analogously for transparent ETFE foils as already described by the equations (1) and (2) in section 3.1. For a simplified approach, it is now assumed that in addition to the emitted portion of a layer, the portion emitted by the previous foil layer must also be taken into account in the form of a reduced transmission. Consequently, the proportion that directly penetrates the foil layer is also added to the emission of the layer (Figure 5.1).

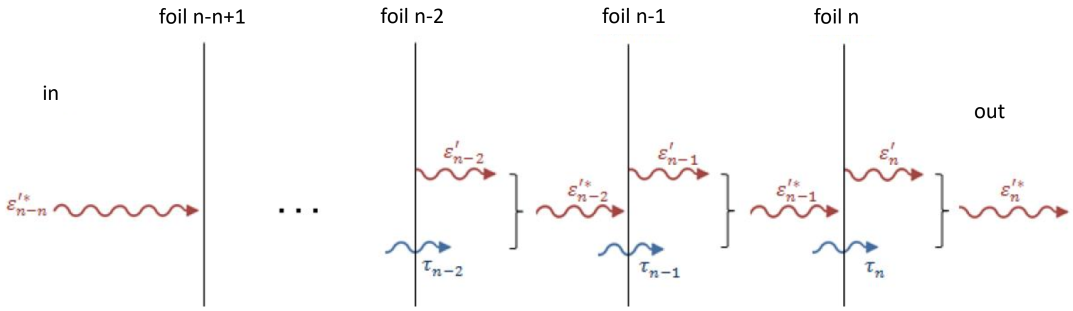

Figure 5.1: Corrected IR emissivity for the ith foil layer[8].

A 3-layer foil cushion's corrected emissivity ε'* can consider its IR transparency by applying equations (4) till (6):

Foil 3: $$\varepsilon_3'^{*} = \varepsilon_3' + \varepsilon_2'^{*} \cdot \tau_3 \tag{4}$$

Foil 2: $$\varepsilon_2'^{*} = \varepsilon_2' + \varepsilon_1'^{*} \cdot \tau_2 \tag{5}$$

Foil 1: $$\varepsilon_1'^{*} = \varepsilon_1' + \varepsilon_0 \cdot \tau_1 \tag{6}$$

Inserting equations (5) and (6) into the 3rd foil's equation (4) the corrected emissivity can be calculated using the combined equation (7). The emissivity ε_i' of any foil layer i can be corrected to consider the systems IR transmittances τ_i facilitating equation (8).

Foil 3: $$\varepsilon_3'^{*} = \varepsilon_3' + (\varepsilon_2' + (\varepsilon_1' + \varepsilon_0 \cdot \tau_1) \cdot \tau_2) \cdot \tau_3 \tag{7}$$

Foil i: $$\varepsilon_i'^{*} = \varepsilon_i' + \varepsilon_{i-1}'^{*} \cdot \tau_i \tag{8}$$

ε_i' emissivity of the ith foil layer on the opposite side of incident radiation

$\varepsilon_i'^{*}$ corrected emissivity considering the foil's IR transmission

In the case of a multilayer system, the corrected emissivity of the previous foil layer must be taken into account to determine the corrected emissivity. In general, the following applies to the corrected emissivity of the nth layer as formulated in equation (9):

Foil n: $$\varepsilon_n'^{*} = \varepsilon_n' + \sum_{i=1}^{n} \varepsilon_{n-i}' \cdot \prod_{j=1}^{i} \tau_{n+1-j} \tag{9}$$

This simplified approach, allows for the IR transmission to be considered with sufficient accuracy. The effects on the calculated U_g-values are discussed in section 5.4.

5.3 Boundary Conditions

The boundary conditions of ISO 6946 and EN 673 are almost identical. Although the surfaces' heat transfer resistances can be determined individually for both standards as a function of the air velocity, emissivity and heat flow direction. Both standards use an external heat transfer resistance of 0.04 (m²K)/W and an internal heat transfer resistance of 0.13 (m²K)/W for the calculation of comparative values.

When calculating according to ISO 15099, the boundary conditions of NFRC 100-2010[13] are usually applied. The boundary conditions specified there differ somewhat from those of the other two standards. The external heat transfer resistance is around 0.03 (m²K)/W and the internal one approx. 0.12 (m²K)/W. In addition, the applied temperature difference between -18°C (outside) and +21°C (inside) is somewhat bigger than that of EN 673, which specifies an average temperature of 10°C and a temperature difference between the outer surfaces of 15 K. This influences the convections and the thermal resistances in the entire construction.

The air's material properties found in both standards (density, thermal conductivity, dynamic viscosity and specific heat) differ slightly, but ultimately doesn't lead to a significant influence on the U_g-value.

5.4 Results

The following diagram (Figure 5.2) compares the results of the different calculation methods and boundary parameters for two identical cushion structures with different outside foils. The material properties of the ETFE foil are identical in all calculations for MEM 1 / MEM 3. The two cushion samples are shown in section 4, Figure 4.2. The boundary conditions and air characteristics used for the calculations are described in section 5.3.

The values of the upper three bars do not take into account the IR transparency. These results were determined based on EN 673 with the program WINDOW, a spreadsheet routine of the company se-cover, as well as on the basis of EN ISO 6946 from Fraunhofer IBP. The values differ only slightly from each other. The differences in the two values according to EN 673 may have their cause in the approach of the average temperature of the air gap and the temperature difference between the adjacent foil surfaces. The spreadsheet routine determines the values iteratively on the basis of the individual thermal resistances for an outside temperature of 0°C and an inside temperature of 20°C.

The values of the bottom three bars take into account transmission in the IR range in different ways. The first of the three bars uses the ISO 15099 calculation method, with the NFRC 100-2010 boundary conditions. In the last two bars, the calculation method of ISO 6946 and EN 673 is supplemented by the simplified method described in section 5.2, which takes IR transmission into account. The difference with ISO 15099 can be justified by the fact that there is a fundamental difference in the calculation procedures.

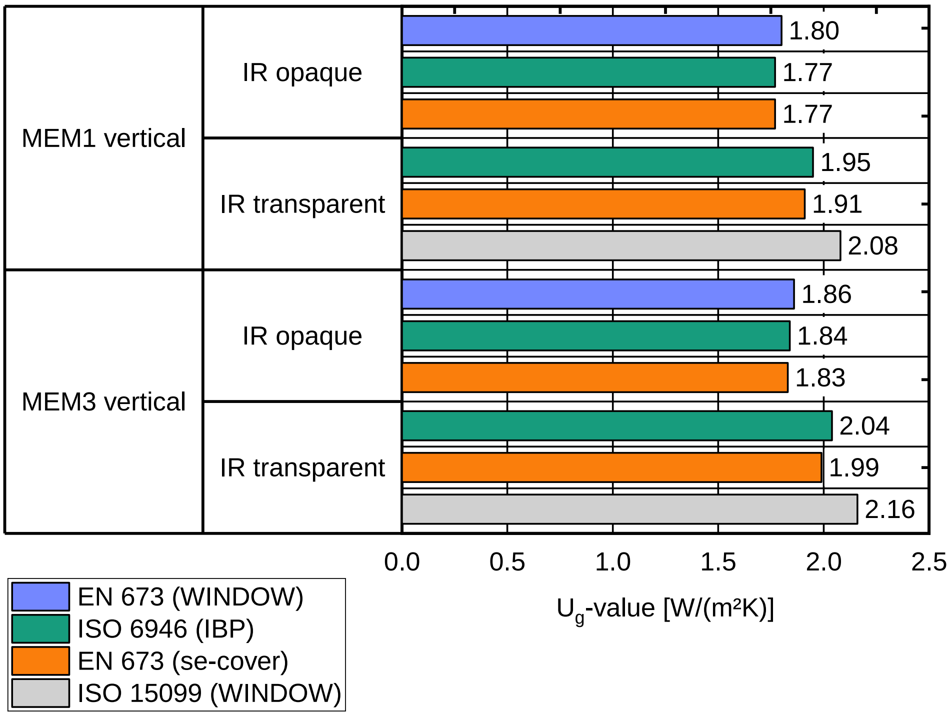

Figure 5.2: Comparison of different standards' calculation results; U_g-value [W/(m²K)].

A comparison of the calculations with and without IR transmission clearly shows that taking IR transmission into account leads to an increase in the U_g-value. By applying a printing, the proportion of IR transmission can be reduced. This also reduces the difference in the calculation methods with and without IR transmission. This is already visible with the low printing of MEM 1 (one layer with 50 %) compared to MEM 3 (without printing).

In situations where the convective part of the heat flux decreases, the radiative fraction of the heat flux increases relatively. This leads to an increase of the difference between calculation methods with and without IR transmission. Figure 5.3 (bottom) shows this effect on cushion MEM 3 for the roof under cooling conditions, with a downward heat flux. The inside temperature is 25°C and the outside temperature is 30°C. The boundary conditions correspond to the specifications of the standard for a downward heat flow (Nu = 1; internal heat transfer resistance 0.17 (m²K)/W). For the air, the characteristic data at 10°C are retained. The difference between the calculation according to EN 673 with and without IR transmission increases from 0.16 W/(m²K) (8.7 %) Figure 5.2 to 0.19 W/(m²K) (11.8 %) Figure 5.3.

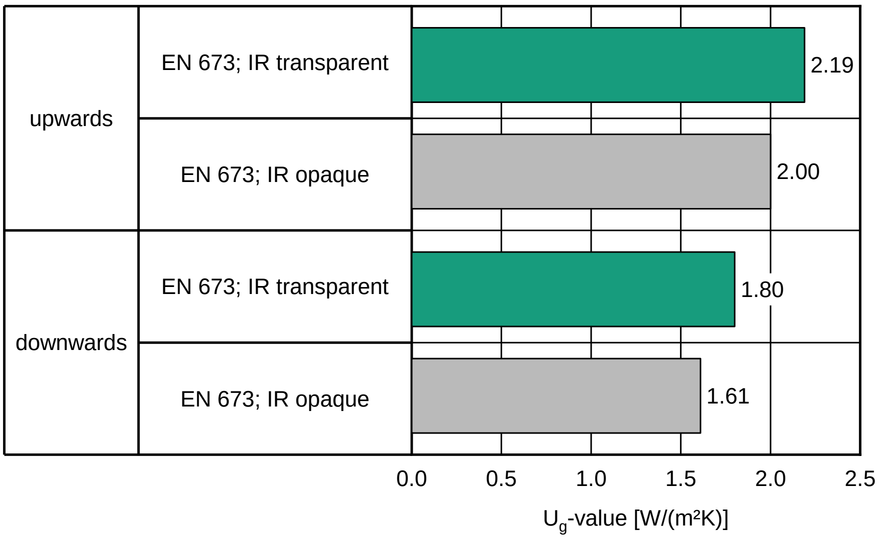

Figure 5.3: Comparison of the MEM 3 calculation results for an upward (top) and a downward (bottom) pointed heat flux; U_g-value in W/(m²K).

Especially projects located in warmer regions, where the cooling case can be the relevant one attention must be paid to the boundary conditions applied. Otherwise an U_g-value for downward heat flux according to EN 673 without IR transmission of 1.61 W/(m²K) (Figure 5.3) is compared with a horizontal heat flux according to ISO 15099 of 2.16 W/(m²K) (Figure 5.2) or with an upward heat flux according to EN 673 with IR transmission of 2.19 W/(m²K). This is especially relevant to HVAC sizing or indoor thermal comfort calculations. When sizing components of the building service systems or ratings the indoor thermal comfort the envelope's thermal properties should reflect the relevant design conditions. So different U_g-values should be considered when sizing a chiller or a boiler.

6 CONCLUSION

Pneumatically supported single-chamber and multi-chamber systems have double-curved cushion surfaces and are subject to variable boundary conditions, such as pressure changes, air flow and changes in the shape of the surfaces. Thus, convection is not constant. The low mass ensures that changing effects are not smoothed out. The calculated U_g-value is therefore, by definition, always only a comparative value and not a real system value. HVAC sizing or indoor thermal comfort calculations should always be performed not with the unified boundaries for product comparison but with boundary conditions reflect the expected actual conditions.

In general, it has been shown that the common calculation methods according to EN 673[2] or ISO 6946[12] can represent ETFE cushion systems with sufficient accuracy, if the infrared transmission properties are taken into account appropriately. This can e.g. done according to the method proposed in this paper, modifying the foils emissivities ε. If the U_g-value is to be used as a comparative value for the thermal transmittance of defined envelope components (roof, façade), care must be taken to ensure that the same calculation method is used, i.e. the same standard and the same boundary conditions. If the design team is nevertheless presented with significantly different U_g-values from different vendors, although the system and boundary conditions were set identically, this is likely caused by different treatments of the IR transparency. One vendor may have added the transmission τ in the IR spectrum according to EN 673 to the emissivity ε or even the reflection ρ, while the other one has properly taken the transmission into account, e.g. according to the method proposed here.

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