THERMOTECHNICAL OPTIMIZATION OF MEMBRANE CLAMP PROFILES REGARDING STATICAL AND ASSEMBLY ENGINEERING ASPECTS

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Key words: clamp profile, thermal bridges, heat protection, risk of mold formation and water condensation, thermal transmittance, minimum surface temperature.

Summary: The thermal optimization of a two-dimensional membrane model is presented, with regard to typical construction features of a clamp profile. Based on a reference profile, measures of building physics like the use of insulation layers but also geometrical variations of the profile have been investigated in detail to reduce the effect of thermal bridges and heat losses. As a result the inside minimum surface temperature can be raised in order to reduce the risk of water condensation. This helps to avoid possible damages to the supporting structures.

The results were used to develop a thermally optimized membrane profile, which meets both assembly engineering and statical requirements. Key features of these profiles are a significant reduction of the thermal transmittance and a complete avoidance of water condensation on the inside surfaces.

1 INTRODUCTION

Recent research reports[1, 2, 3] show that the requirements of heat protection and protection against moisture cannot be totally fulfilled by conventional membrane constructions. The investigated multilayer foil constructions are able to ensure the minimum thermal protection, but there is a significant loss of energy at the clamp profiles as a result of the geometrical and material specific constraints and boundary conditions.

This paper presents the development of optimized membrane profiles regarding assembly engineering and statical requirements. Different variables for the thermally optimized clamp profile are presented and evaluated in serveral geometrical and building physics variation steps for the chosen reference profile. Thereby the International Standards for window contruction are used to determine the characteristic thermal values since there is presently no standard for membrane contructions.

2 REQUIRED CHARACTERISITC VALUES OF BUILDING PHYSICS

2.1 Characteristic thermal values

The thermal transmittance (U-value) is a significant variable of the thermal insulation of building structures. The U-value of windows, doors and shutters is calculated using DIN EN ISO 10077-2[4] and defined as:

$$U_f = (L_f^{2D} - U_P * b_P) / b_f \qquad [W/(m^2\,K)] \qquad (1)$$

2.1 Characteristic hygrothermal values

The thermal bridges in clamp profiles are causing both high heat flows and low surface temperatures. The knowledge of these low surface temperatures is necessary to evaluate the risk of water condensation and mold formation[6].

The temperature factor f (f-value) is defined as the difference between the interior surface temperature of a component and the exterior air temperature, related to the difference of interior and exterior air temperature[7, 8].

$$f_{Rsi} = \frac{(\theta_{si} - \theta_e)}{(\theta_i - \theta_e)} \qquad [-] \qquad (4)$$

A temperature field of the building structure, including an isothermal curve and a color scale, is used to show the specific temperature conditions of a profile. *Red* represents the maximum and *purple* the minimum temperature.

The following simulation is based on the characteristic boundary conditions (cf. table 1) according DIN 4108-2[7]. To avoid water condensation on the inner surface of the construction the 9.3°C-isothermal curve should be located in the interior profile. This curve is illustrated as a bold black line (cf. figure 1).

Table 1: Boundary conditions according DIN 4108-2

area	temperature	relative humidity
indoor climate	20 °C	50%
outdoor climate	- 5 °C	-

Under these boundary conditions there is a high risk of mold formation when the surface temperature is lower than 12.6°C. The 12.6°C-isothermal curve is shown as a red line (cf. figure 1). In table 2 the minimum surface temperatures and temperature factors for the risk of mold formation and water condensation are described.

Table 2: Minimum surface temperatures θ_{si} and temperature factors f_{Rsi} for the risk of mold formation and water condensation

effect	$\theta_{si,\,min}$	f_{Rsi}-value
mold formation	12.6 °C	0.70
water condensation	9.3 °C	0.57

3 THERMAL ANALYSIS OF THE REFERENCE PROFILE

Two types of the chosen reference profile are analysed, with and without screw joints to the supporting structure. There are three different types of supporting structures which are included in the simulation process according [5]. This paper's focus is the clamp profile without a fixing in between the supporting structure. The other types of supporting structure, the clamp profile with a steel support and the clamp profile with a continuous supporting structure on a wooden cross-section are not explained further. All measurement data is reported in millimetre.

Figure 1 shows the sectional drawing and the temperature field of the reference profile with *(upper picture)* and without screw joints *(lower picture)*. The temperature field for the profile with screw joints is indicating a minimum surface temperature $\theta_{si,\,min}$ of 7.5°C. Water condensation can occur on the inside surface. The f-value is 0.50.

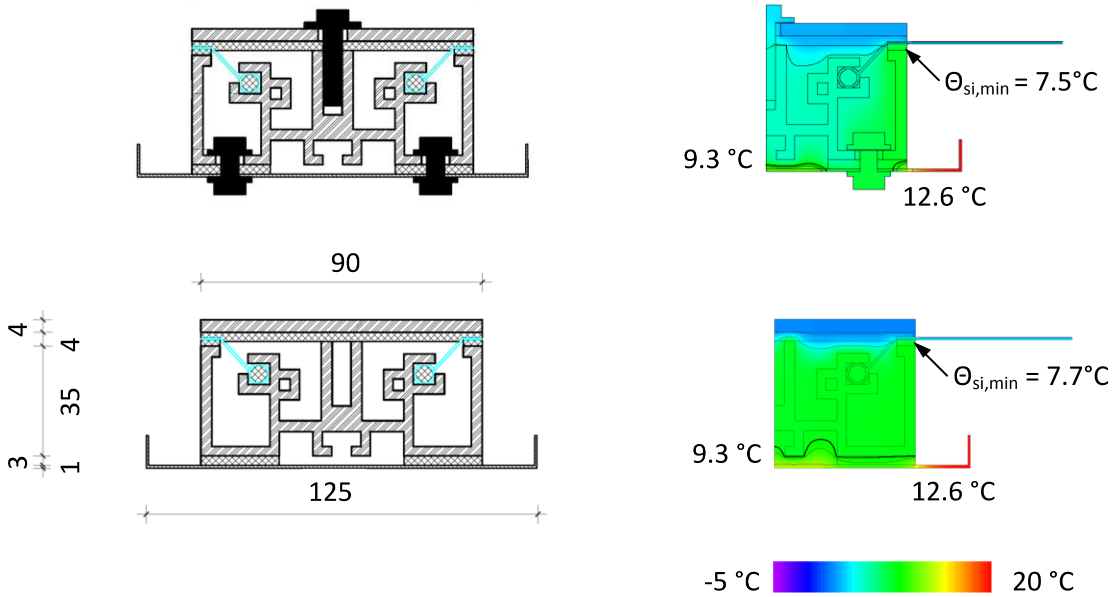


Figure 1: Sectional drawing and temperature field of the reference profile with (*upper picture*) and without (*lower picture*) screw joints

Compared to the usual thermal transmittance for window frames, a U_f-value of 9.2 W/(m² K) for the profile with screw joints is high and thus representing a large thermal bridge. Without screw joints the values aren't significantly better; however water condensation occurs. The U_f-value for the entire profile is 7.7 W/(m² K).

4 OPTIMIZATION PROCESS

In the following chapter the most efficient strategies for the optimization of the chosen reference profile are presented. Detailed analyses [5] show the following results:

By filling polyurethane foam (thermal conductivity 0.030 W/(m K)) in the profile cavity, there is no significant improvement of the U_f-values and the minimum surface temperature. This may be due to the fact that the biggest heat loss is taking place over the screw joints of the central aluminum fin which is continuing to the supporting structure. A probable assumption is that insulating the cavity has no influence on the heat flow through screw joints and the central fin. Further analyses are confirming this assumption.

The lateral insulation of the interior profile surface (thickness = 2 cm, thermal conductivity 0.030 W/(m K)) does also not result in a reduced risk of water condensation. The application of a lateral insulation leads only to an improved U_f-value (4.7 W/(m K)), whereas the surface temperature is falling below the temperature of the reference profile. This difference can cause an increased risk of water condensation.

The warm air of the room cannot contribute to the warming up of the construction from inside as the contact surface to the good heat-conducting aluminum is reduced.

4.1 Exterior insulation of the profile cover plate

In the following this optimization strategy is titled *insulation cover plate.* An insulation layer (thickness = 1 cm) is placed at the rear side of the cover plate (thermal conductivity = 0.035 W/(m K)). This strategy results in the temperature fields shown in figure 2.

The minimum temperature of the profile with screw joints is 9.0°C and thus 1.5 °C higher than the temperature of the reference profile. The f-value is 0.56. Without screw joints the minimum surface temperature adds up to 13.0°C. Regarding the given boundary conditions in table 1 there would occur no water condensation.

The U_f-value of the profile with screw joints decreases in this case to 9.0 W/(m² K) compared to the reference profile with 9.2 W/(m² K). This results in a U_f-value of 3.4 W/(m² K) for the entire profile. Although the screw head has only a small contact to the outside, the thermal conduction is relatively high because of the high thermal conductivity of steal. The central aluminum fin increases the heat flow to the outside of the profile. This effect was also observed for the filled cavity profiles. Due to the lower thermal transmittance of the profile without supporting structure, the U_f-value is about 60 % lower than the one of the profile with screw joints. The screw joints of the cover plate and the central aluminum fin have the highest influence on the heat flows to the outside. These results have to be considered in the further optimization process.

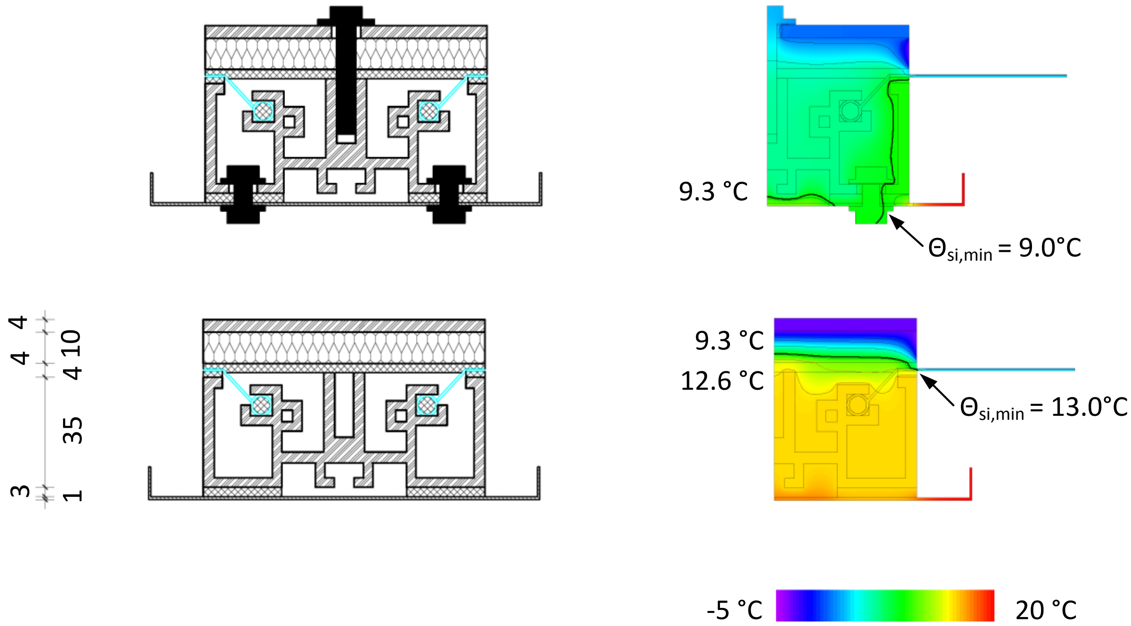


Figure 2: Sectional drawing and temperature field of the reference profile for the optimization case *insulation cover plate* with (*upper picture*) and without (*lower picture*) screw joints

4.2 Separated foil layers with additional aluminum clamps

In the following this optimization strategy is called *foil spacers*. In this simulation two additional aluminum profiles are installed for the foil layers. Their geometrical structure is based on the reference profile. This measure results in a cumulative construction hight of 75 mm. In figure 3 the corresponding temperature field for this profile is visualized.

This case is a first step to investigate the optimization potential for separated foil layers. The possibility of a practical application regarding the air tightness of pneumatic membrane constructions will be investigated in a following chapter.

The minimum surface temperature with screw joints is 8.8 °C and therefore 1.3°C higher than for the reference profile. The f-value is 0.55. The U_f -value for the profile with screw joints has increased only slightly to 9.7 W/(m² K), compared to the reference profile (9.2 W/m² K). The U_f -value for the entire profile-system is 7.8 W/(m² K). The characteristic values show that the separation of the foil layers does not significantly improve the minimum surface temperature, but the curve progression of the isothermal curves is more homogeneous. Hence, the additional aluminum profiles do not improve the thermal insulation because of the high thermal conductivity of the central fins and their side walls.

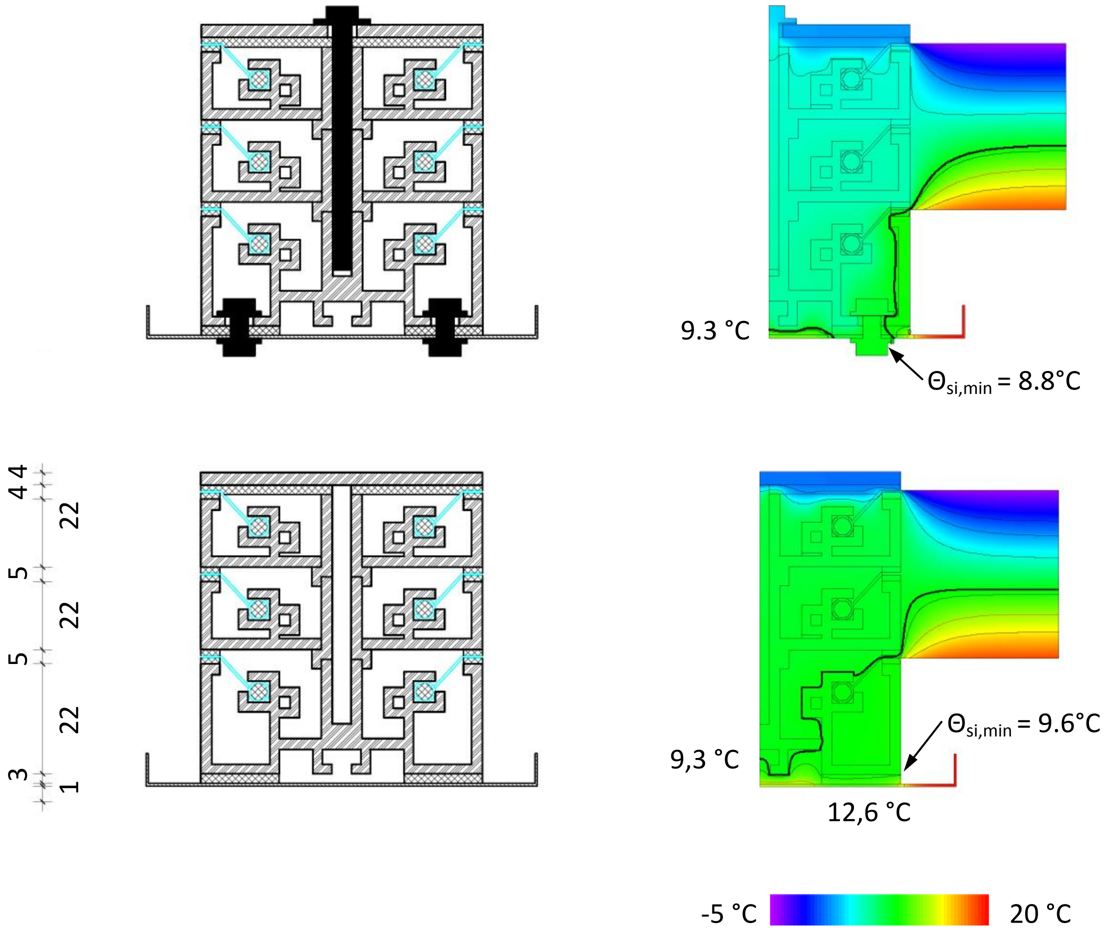


Figure 3: Sectional drawing and temperature field of the reference profile for optimization stratgey *foil spacers* with (upper picture) and without (lower picture) screw joints

4.3 Plastics for the profile construction

In the following text this optimization strategy is titled *plastic profile*. Unplasticized polyvinyl chloride (PVC) is a common material for window constructions. Especially the low thermal conductivity (0.17 W/(m K)) leads to reduced heat losses.

As shown in the previous chapter, a particularly high heat loss is caused by aluminum profiles. Due to the fact that plastic material has a low strength, a reinforcement section is necessary (e.g. out of aluminum). The position and thickness of the reinforcement section as well as the number and order of cavities in the profile are essential for the thermal transmittance[9, 10]. This optimization strategy results in the temperature fields shown in figure 4.

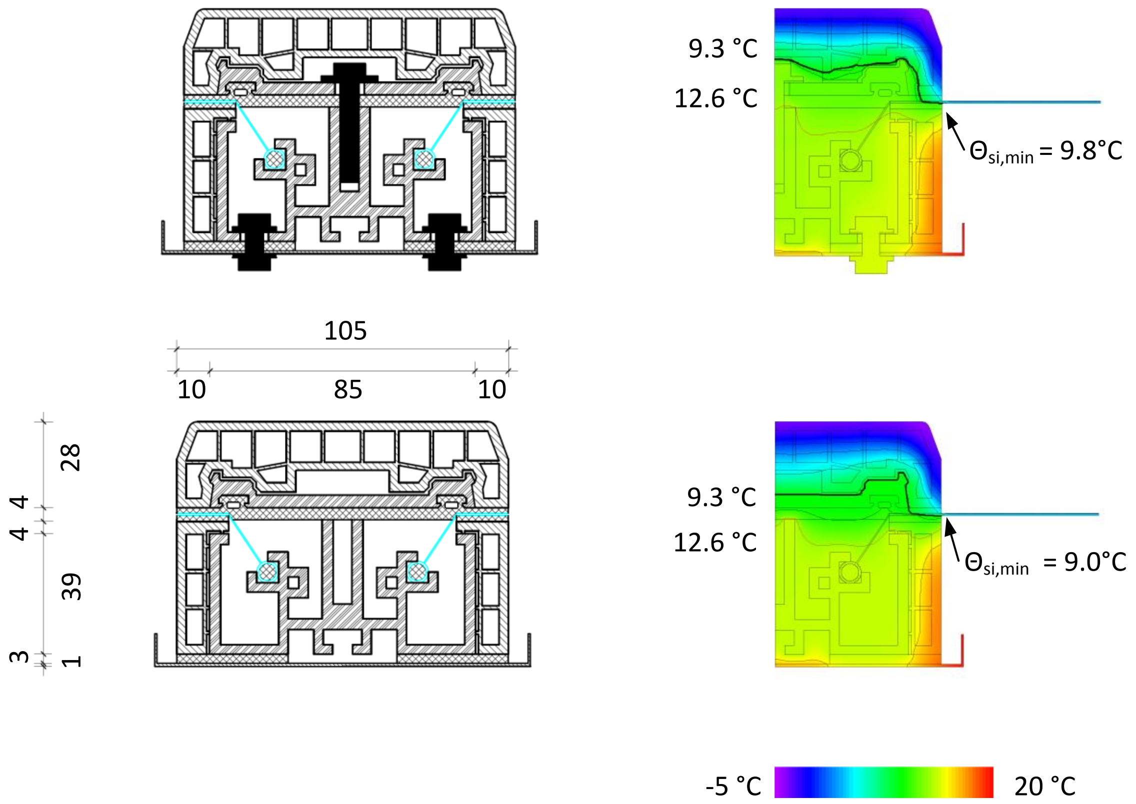


Figure 4: Sectional drawing and temperature field of the reference profile for optimization strategy *plastic profile* with (*upper picture*) and without (*lower picture*) screw joints

The minimum surface temperature in the case of screw joints is 9.8°C. Hence, there is no more risk of water condensation. The f-value is 0.59.

In comparison to the reference profile (U_f = 9.2 W/(m² K)), the U_f-value for the profile with screw joints is reduced to 3.9 W/(m² K) and the total profile has a U-value of 3.4 W/(m² K). By constructing an external insulation made from plastic material, the cover plate screw joint is insulated and decoupled. Better results are obtained. The implementation of a plastic frame with aluminum reinforcement can lead to a reduction of the thermal transmittance for the entire profile of 55%. Moreover it can be seen in figure 4 that the 9.3°C-isothermal curve is close to the edge of the profile. Only in the transition area between foil and clamp profile the curve extend into the interior side, which would enhance the formation of water condensation.

5 DEVELOPMENT OF A THERMALLY OPTIMIZED CLAMP PROFILE

5.1 Most promising optimization method and its practical implementation

Regarding the reduction of the thermal transmittance and the increase of the minimum surface temperature the installation of an exterior insulation layer offers the biggest room for improvemwnt. This improvement can be achieved by insulating the cover plate with a 1.0 cm thick layer or insulation a PVC-cover plate, which includes cavities.

An insulation layer beneath the cover plate is of no practical use since the foil layers move as a result of the interacting forces.

The clamp profile cover plate offers a consistent contact pressure on the membrane foil layers; similarly the EPDM-layers seal the profile against water and other environmental impacts. Therefore a PVC-cover plate, including cavities, will be chosen.

Although the separation of foil layers with an aluminum construction leads to a higher thermal transmittance, the highest minimum surface temperatures can be reached with the above mentioned strategy. Using this method, the 9.3°C-isothermal curve can be shifted to the inside of the profile. Thereby the risk of water condensation can be minimized, as function of the above mentioned boundary conditions (cf. table 1). Therefore a separation of foil layers will be considered for the development of a thermally optimized clamp profile.

5.2 Installation of foil spacers and insulation of the cover plate

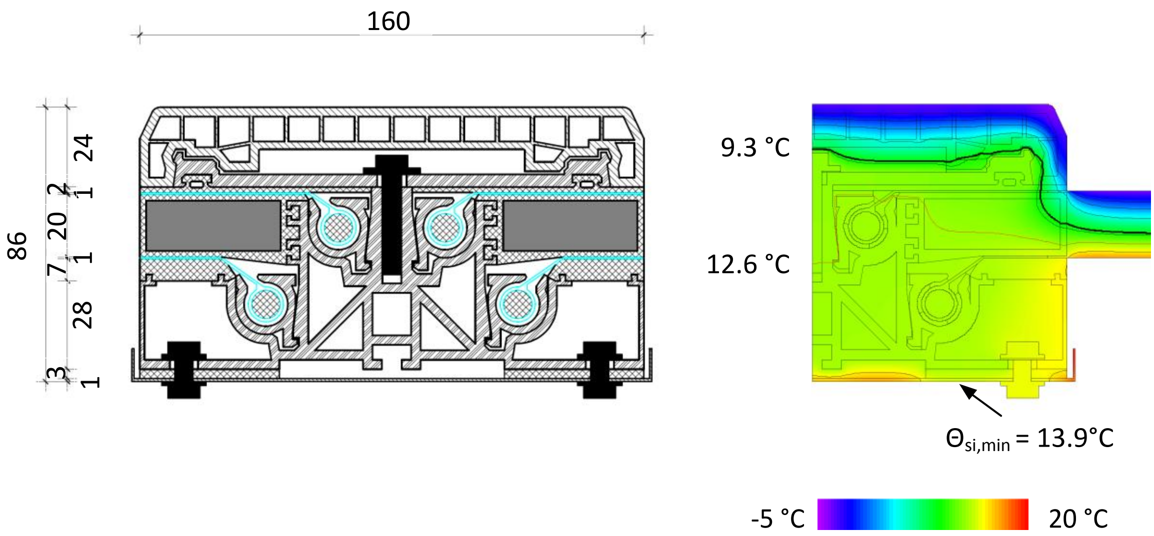
In the following chapter this optimization strategy is titled *foil spacers and insulation cover plate*.

The analyses in the previous chapter have shown that the separation of foil layers leads to a higher minimum surface temperature and thus a reduced risk for the occurrence of water condensation. The installation of a cover plate profile made from PVC with aluminum reinforcements is resulting in a reduction of the U_f-value and an improvement of the minimum surface temperature.

A profile is developed to combine these two optimization strategies. In order to avoid a too large profile width or hight, two clamp devices for each profile side are designed.
Due to the fact, that a three-ply foil construction is used, there is for example the possibility to weld and clamp two foils separately from the third one.

Furthermore the use of two clamp devices makes it possible to assemble different types of foils, for instance a foil implementing a sun protection without the necessity for a common cord edge.

This can be beneficial regarding production as well as assembly and maintenance.



U_f	3.4	[W/m² K)]
$\Theta_{si,min}$	13.9	[°C]
f_{Rsi}	0.76	[-]

Figure 5: Sectional drawing, the temperature field and the building physics specific values of the optimized clamp profile with foil spacers and insulation cover plate with screw joints

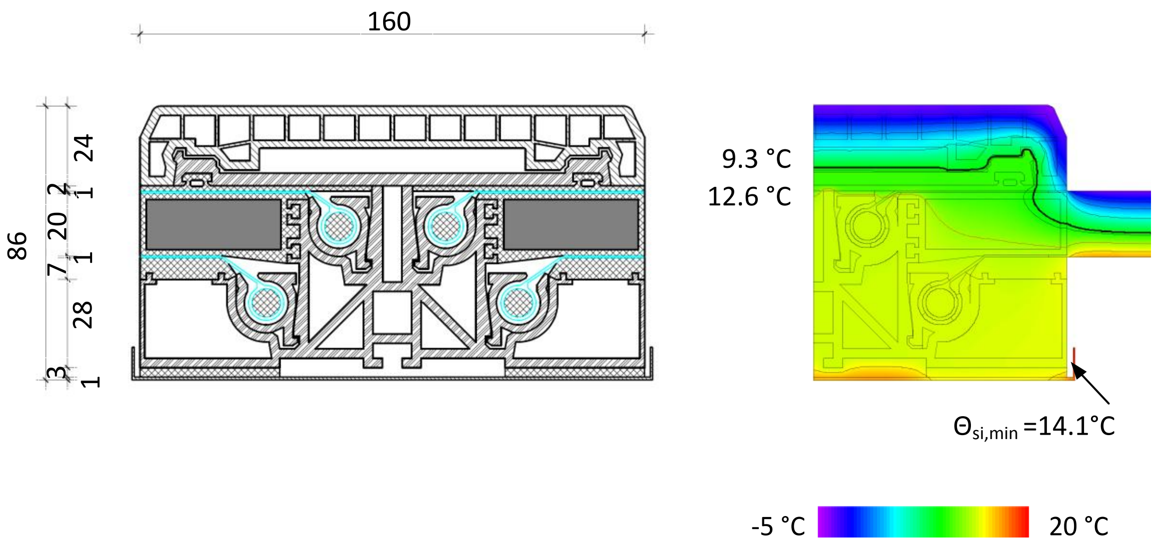
The spacer can be made out of composite material. On the one hand the exterior layer has to be elastic and caulking to equalize foil movements and to guarantee an air tight pneumatic foil construction. On the other hand two important requirements for the interior construction are thermal insulation as well as load reduction. The use of foamed EPDM and reinforcements as for example glass fiber reinforced plastics can help to accomplish the required characteristics.

To guarantee an air tight pneumatic foil construction, butt joints of the profile sections (in longitudinal direction) have to be avoided. Therefore, a tongue-and groove-joint could be used. As the required spacer should be further analyzed regarding its practical usefulness, there is no specification of a construction material in the following chapter.

The figures 5 and 6 show the sectional drawing, the temperature field and the building physics specific values of the optimized clamp profile with foil spacers and insulation cover plate with and without screw joints.

In this considered case the minimum temperature amounts to 13.9 °C and results in an f-value of 0.76 (with screw joints). Compared to the reference profile the minimum surface temperature decreases by 6.4°C. The course of the 9.3°C – isothermal curve is close to the edge of the profile cross-section, but remains in the profile. Therefore there is no risk of water condensation. The minimum surface temperature is located at the bottom inside of the clamp profile.

The U_f-value of the total profile drops from 7.7 to 3.0 W/ (m² K) compared to the reference profile. This means an improvement of 61%.



U_f	3.0	[W/(m² K)]
$\Theta_{si,min}$	14.1	[°C]
f_{Rsi}	0.76	[-]

Figure 6: Sectional drawing, the temperature field and the building physics specific values of the optimized clamp profile with foil spacers and insulation cover plate without screw joints

The installation of foil spacers in combination with the insulation of the cover plate results in a considerable improvement of the thermal transmittance. The risk of mold formation and water condensation for standard boundary conditions is eliminated. Due to the fact that the weak points in the foil connecting area are resolved, the minimum surface temperature is not located in the transition of the foil connecting area any more.

12 CONCLUSION

To determine the likelihood of water condensation in membrane clamp profiles, it is necessary to consider the thermal transmittance as well as the minimum surface temperature. A thermal bridge analysis of the chosen reference profile is indicating the biggest heat losses in the profile cross-section. It is shown that the transition area from the clamp profile to the foil layer construction is a weak point as well as the central profile fin. Changes in building physics parameters as well as geometrical parameters lead to improved characteristic values. A reduction of the thermal transmittance is not coercively resulting in higher minimum surface temperature inside the profile and vice versa.

A combination of the most efficient strategies leads to a thermally optimized membrane clamp profile. The profile with separated foil layers and a decoupled profile cover plate shows the best results.

With regard to the thermal characteristic values, there is a large improvement, which leads to the avoidance of water condensation and a significantly reduced thermal transmittance.

As shown it is possible to combine different optimization strategies in order to provide a thermally optimized clamp profile with regard to statical and assembly engineering aspects.

Based on the results of this paper future analyses can be conducted and tested in context of practical applicability.

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