Modelling of Complex Fenestration Systems – Validation Results by Long-Term Measured Data

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Abstract

This paper shows comparative results between simulated and measured values on a complex façade system. The simulation was carried out with the newly implemented model in TRNSYS for complex glazing systems based on the ISO 15099 standard and using BSDF data. Long-term measurements were done on a test façade under real weather conditions. Investigations were made on a major diffuse-reflecting and a highly specular blind system to examine the model capabilities. We compared modelled and simulated layers and air gap temperatures. The overall model results show a satisfying correlation. Nevertheless, model simplifications are reflected in the results and discussed in the conclusion of the paper.

1. Introduction

An integral evaluation of thermal and daylighting performance of complex façade systems (CFS) is a crucial aspect to achieve optimized results in minimizing the energy demand of heating, cooling, and artificial light, while enhancing thermal und visual comfort. By implementing the RADIANCE flux matrix methods, an efficient annual daylight simulation even for complex fenestration systems could be achieved. Therefore, a new model algorithm "ArtLight 2.0" was implemented in TRNSYS in order to enable coupled thermal and daylight simulations with efficient run times in the dynamic building simulation (Hauer et al., 2015).

For the daylight modelling as well as for the thermal modelling, the bi-directional scattering distribution function (BSDF) is used to treat the transmitted part of the incident radiation. For the thermal part a flexible approach was introduced by Klems (Klems, 1994a, 1994b) to calculate the bi-directional solar transmittance of a CFS by multiplying several matrices - each representing a layer of the complex glazing setup. The hemispherical front and back side of a shading layer is discretized into 145 patches, which allows the description of the transmittance behavior by 145 ingoing and outgoing directions.

For the detailed longwave radiation modelling, the algorithms according to ISO 15099 are used. The detailed longwave radiation exchange between glazing layers and non-planar layers (e.g. shading blinds, screens...) is calculated using "layer-equivalent" parameters specifying the thermal characteristics, based on LBNLs layer-method. This includes the thermal emissivity (front and back) as well as the infrared transmittance of such a non-planar layer. Additionally, a dimensionless and almost free to choose front openness factor describes the permeability of the shading and subsequently its influence on the convective air circulation around and through the slat stack.

Although these model algorithms tend to describe the physical phenomena in detail, a fundamental comparison and validation against measured data is still rarely available in the literature. First, detailed verifications of mathematical models describing complex shades against measurements were carried out within the framework of the IEA Task 34/Annex34. This comprehensive work, conducted by different research laboratories around Europe, included several simulation tools (EnergyPlus, DOE-2, ESP-r, TRNSYS). Results and conclusions are found

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in several publications (Loutzenhiser et al., 2008; Simmler and Binder, 2008).

Nevertheless, the testing in the previously mentioned studies was short-term and supposed to cover almost ideal situations (e.g., clear sky or cloudy sky) for a significant model validation. Furthermore, the modeling capabilities have improved significantly by the initially mentioned methods in the last years - especially in terms of modelling complex daylight re-directing blinds.

The present work contributes to the comparison and validation of a newly introduced CFS modelling method in TRNSYS Type56 (Hiller and Schöttl, 2014). Within the Austrian national research project "lightSIMheat", beside several simplified approaches, this method is used as a thermal modelling part within the coupled ArtLight-routine. In cooperation with SFL technologies in Stallhofen an extensive long-term monitoring on different façade types was carried outto test these models under real environmental conditions.

2. Thermal Modelling of CFS

2.1 Type56_BSDF in TRNSYS

The latest model implementations based on bi-directional scattering distribution functions (BSDF) are available (Hiller and Schöttl, 2014) for the detailed thermal modelling of CFS within the multi-zone building model in TRNSYS. In contrast to the previous standard window model based on one-dimensional angular dependent input values for transmission, reflection and absorption (WIN-DOE file), the new model uses BSDF-data. (Fig. 1). This enables a detailed optical modelling of multiple scattered reflection and transmission of blind systems - especially in case of specular, daylight redirecting systems. Subsequently, a detailed thermal modelling is done according to the algorithms defined by ISO 15099 standard. Based on the established concept of a layer-by-layer calculation for glazing systems (Fig. 2), the shading blind is thermally treated as a homogenous layer by pre-calculated factors for infrared transparency and effective emissivity that define the longwave radiative exchange. The modelling of the convective behavior around the shading layer is simply covered by an effective openness factor that describes the "permeability" of the slat stack. These values are calculated for each slat angle.

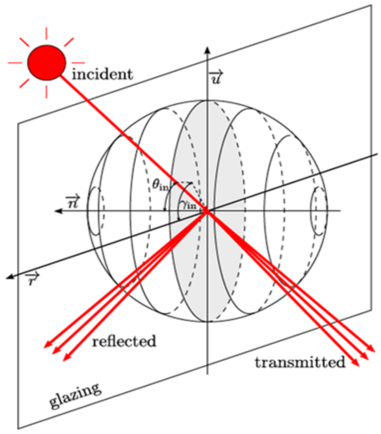

Fig. 1 – Thermal modelling of transmitted solar gains by BSDF datasets (Hiller and Schöttl, 2014)

A comparison between the BSDF-model and the simplified approaches was presented at the Building Simulation Application Conference 2015 in Bolzano (Hauer et al., 2015). As a further step these models are now validated in terms of accuracy and practicability against long-term measurement data from a real office façade carried out within the present work.

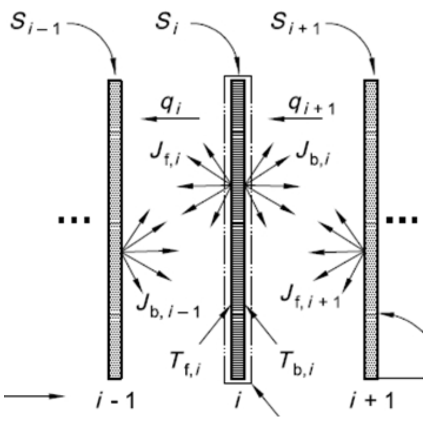

Fig. 2 – Layer-by-layer modelling according to ISO 15099

3. Monitoring

3.1 Façade Description

The monitoring façade is located in one of the Cell-Labs of SFL technologies GmbH (Fig. 3) in Stallhofen/Austria. The Cell Lab is a cubic space with glazing and opaque façade elements in two directions (west and south). The south façade with an exact orientation towards south-south-east (Azimuth = 335°) is an experimental façade that includes different function modules (BIST, BIPV, shading, fan coil) (Mach et al., 2015). The east and north enclosures are convertible internal office walls.

Fig. 3 – Cell-Lab at areal of SFL technologies GmbH

The measurement took place in the south façade within a transparent façade element consisting of a room-height window layer (thermally separated aluminum profiles) as thermal envelope with a rear ventilated impact pane at approx. 150 mm distance to the inner window layer. The window layer consists of a lower door and a fixed overhead window, both with a triple-pane insulated glazing.
The impact pane is made of a 12 mm thick double-layer laminated safety glass. The proper description of the window layer setup is documented in Table 1.
The investigated venetian blind is mounted between the window layer and the impact pane. During testing the rear ventilation was blocked by an airtight sealing tape.

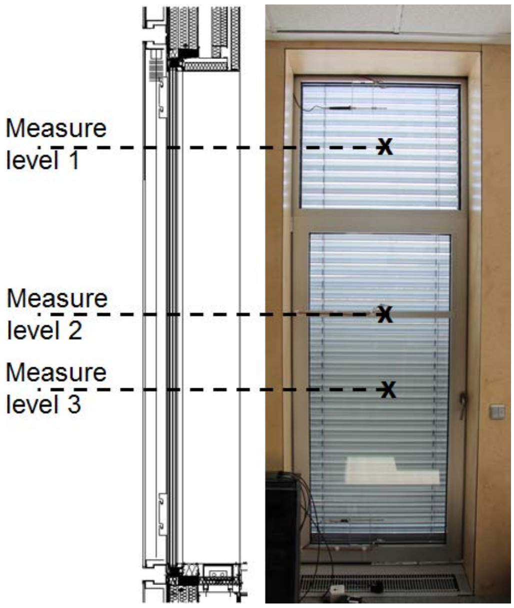

Fig. 4 – Height levels of measurement at the test façade

3.2 Sensor Positions and Radiation Measurements

Sensors were mounted at three different height levels in the façade (Fig. 4) in order to verify differences in the temperature profile over the height. Fig. 5 schematically shows the sensor positions along the façade depth at the different levels. Naming is as follows: the first number indicates the height level; the second number the corresponding system-layer.
Sensors for surface temperatures (OT, Pt100-type 1/3 DIN B) at glazing and blind were mounted on the front and back side of the respective layer (except the outer side of the safety glass): OT10 - OT16 for level 1 and OT30 - OT36 for level 3. On level 2 no surface temperature sensors were used.
Sensors for air temperature (LT, Pt100-type 1/3 DIN B) are situated within the air gap in front and behind the blind stack: LT12 – LT14 for level 1 and LT32 – LT34 for level 3. Additional air sensors in front of the impact pane and behind the windows (seen from outside) are positioned to determine boundary temperatures for the model setup (LT20, LT17, LT27, LT37, LT00).
The vertical airflow velocity is recorded within the air gap between impact pane and blind stack (LT/LG21) respectively on the inner side along the triple-pane glazing (LT26/LG26) on level 2 by hot wire anemometers. These sensors also measured the

air temperature (Ahlborn Almemo FVA935TH4, 0,05–0,2 m/s, bidirectional, resolution 0,0001 m/s, accuracy +/-0,04 m/s).

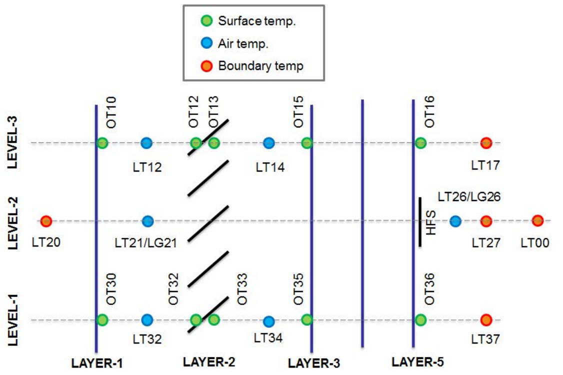

Fig. 5 – Sensor positions on the three measuring levels

Additionally, a heat flux plate (HFS) was mounted on the inner side of the glazing to detect the heat flow to the inside (just valid in times without irradiance on the flux plate).

Irradiance was determined by a secondary standard temperature compensated pyranometer (Kipp & Zonen CMP11) at 285–2800 nm, 0–4.000 W/m², IT_CMP11). In addition, a Daylight measuring instrument (LM-TLM) from company Zumtobel was installed on the rooftop to measure the vertical illuminances for each direction as well as the direct and diffuse component for horizontal illuminance. Thus, the direct-diffuse ratio by the illuminance values was used to split the irradiance value of the CMP11.

During the measuring period a non-standard complex pyranometer with excellent standards was added (Sunshine SPN1, 400–2700 nm, 0–2.000 W/m², IT_SPN1). SPN1 was able to measure direct and diffuse irradiance by means of seven sensors and a shadow ring, which results in one sensor unshaded and one totally shaded, while the others are partly shaded in each measurement. Thus the respective values could be calculated. The vertical global irradiation (perpendicular to the facade) was also measured for the validation of the model by a photo diode sensor, that doesn´t cover the whole solar spectrum (EMS11, calibrated in comparison with Kipp & Zonen CMP12, IT_FAS).

In Fig. 6 a comparison between the reference measurements in the façade (IT_FAS), the simulated radiation based on horizontal measurements with the CMP11 (IT_CMP11) respectively SPN1 (IT_SPN1) are diagramed. Both simulated values show an excellent accordance, even in clear sky as well as in cloudy days. A constant lower measurement result for the vertical global irradiation on the façade (IT_FAS) by photo diode sensor can be mentioned, which can also be partly caused through dust on the sensor.

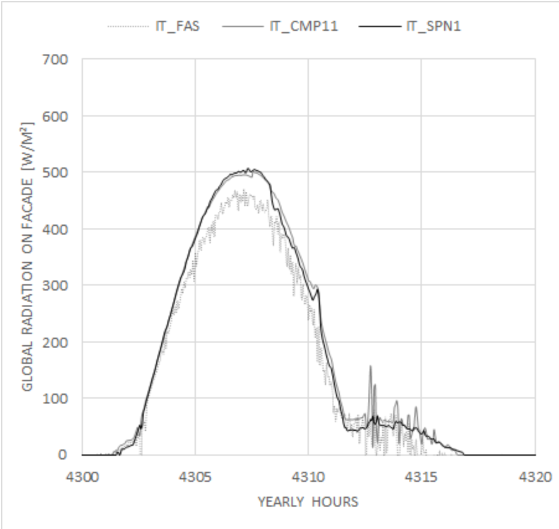

Fig. 6 - Irradiance on Facade: measured vs. simulated

For the model input, the actual radiation on the vertical test façade, which is SSE-oriented (Azi=335°), was calculated based on the measurements by using the Perez 1999 model in TRNSYS Type99.

To get realistic assumptions for the convective heat transfer coefficient, wind velocity and direction on the outer façade were measured by an ultrasonic-sensor, installed in vertical façade orientation (Gill Windsonic, 0–60 m/s, resolution 0,01 m/s, accuracy +/-2 % at 12 m/s, 360 degrees, north facing upwards).

4. Model setup

4.1 System Description Data Acquisition

The system setup of the CFS was done in WINDOW7 according to the glazing layer definition available from manufacturers (Table 1).

Table 1 – Monitoring facade at SFL - layer setup and configuration in WINDOW7

Layer	ID	Product	d
1	893	Impact pane	12 mm
2	1	Shader + Air gap	150 mm
3	11006	Planilux*	6 mm
	9	Air/Argon (10 %/90 %)	16 mm
4	11393	Planitherm One*	4 mm
	9	Air/Argon (10 %/90 %)	16 mm
5	11398	Planitherm One II*	6 mm

*Manufacturer: Saint-Gobain

For the monitoring phase two different blind systems were investigated: one diffuse reflective blind with a non-curved geometry and a concave (upward-curved) blind with a highly specular surface on the upper slat side.
According to the geometrical model of the blind, the BSDF dataset was modelled with the RADIANCE tool genBSDF.

Table 2 – Blind Definition

	SYS 1	SYS 2
width	80 mm	80 mm
spacing	72 mm	46 mm
rise	15 mm	11 mm
ε_{front}	0.69	0.04
ε_{back}	0.93	0.80
material$_{front}$	Millfinish MP	Miro3
material$_{back}$	RAL7035	RAL7030

The layer-equivalent factors for the thermal specification of the BSDF-layer are calculated using WINDOW7. The calculation of these factors is based on the view-factor-method and is calculated internally in WINDOW7 by using blinds defined by their geometrical dimensions (Hauer et al., 2014). Through the modelling a geometrically representative slat and their blind material properties (Table 2), the required factors for infrared transparency (TIR), layer emissivity front (eps_f) and layer emissivity back (eps_b) are determined to define the thermal characteristic of the BSDF-layer (Table 3).

Table 3 – Results for the effective layer specifications

SYS-1	00deg	45deg	85deg
TIR	0.3565	0.2392	0.0020
eps_f	0.5823	0.5957	0.7097
eps_b	0.5823	0.7256	0.9391
EOF	0.95	0.5	0.05
SYS-2			
TIR	0.3250	0.1817	0.0037
eps_f	0.5385	0.4447	0.04
eps_b	0.5385	0.6900	0.8098
EOF	0.95	0.5	0.05

The effective openness factor (EOF) that describes the permeability of the shading layer concerning convection (0=air tight, 1=fully permeable) is treated linear corresponding to the slat angle. Several investigations showed a very low influence of the EOF on the results, while the other thermal parameters showed a clear higher influence.
After including these factors into the modelled System-BSDF file and combining them with the glazing layers according to Table 1, a representative BSDF set for the whole CFS was generated and implemented in Type56_BSDF.

4.2 Façade Model Setup in Type56

The thermal model that represents the measuring site includes the outside oriented glazing façade (BSDF-model) and adiabatic walls in all other directions. The geometric expansion in depth (0.175 m) describes the reveal of the window (cf. Fig. 4). The emissivity values of the walls are equally set to 1 and the construction kept massless.
The setting of the model boundary conditions is shown in Fig. 7. The best agreement between measured and simulated values could be achieved by using the measured temperature directly in front of the façade (LT20) as the external model temperature, instead of using the measured ambient temperature on the rooftop.
Exterior sky-temperature and the ground-temperature were set equal to the measured

ambient temperature. For the boundary conditions on the inner side of the model, the mean value between the measured air temperatures directly behind the inner glazing (LT17/27/37) was used. This showed a better accordance between measured and simulated values than with the measured air temperature in the room behind. Additionally, the back wall of the thermal model was connected with the measured back-wall temperature of the room.

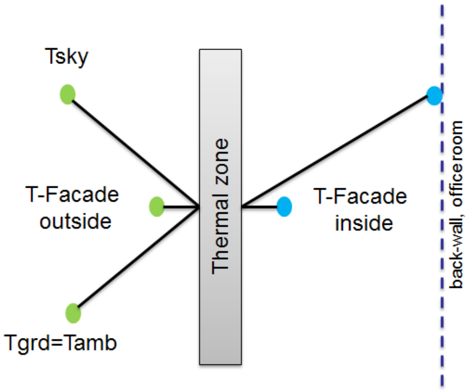

Fig. 7 – Boundary conditions for the thermal model

To model the convective heat transfer coefficient on the outer and inner side of the façade most accurately, an available model in TRNSYS library (Type1232) was used. It calculated an hourly value for the heat transfer coefficient on a vertical flat-plate according to ambient temperature on the surface (outside: LT20; inside: mean value of LT17/27/37), temperature of the surface (outside: mean value of OT30/OT10; inside: mean value of OT16/OT36), as well as the measured air velocities on the outer and inner glazing surface. After implementing these values in the BSDF model of Type56, the results improved significantly, especially for the inner and outer glazing surface temperatures.

5. Results

5.1 System 1

For system 1, several measuring periods were investigated for slat angles of 0°/45° and 85° (fully closed). The comparison of the measurements against the simulation model was done for each layer temperature as well as for the gap temperatures before and behind the slat stack.

Fig. 8 shows a weekly trend of the measured slat temperature (measured on back side) and a tilt angle of 45° compared to the simulations. Especially the rise of the temperature shows a very good agreement. The model underestimates the maximum temperature slightly, although the difference is almost less than 5 K. Due to missing thermal capacity in the blind model, the simulated values fluctuate much more according to the changing irradiance values. The mean deviation between measurement and simulation is in the range of ±5 K.

5.2 System 2

In a second monitoring phase, measurements on system 2 were evaluated similarly for the slat angles of 0°/45° and 85° (fully closed). Fig. 9 shows the weekly temperature trend of the slat temperature (measured on the back side) for a slat angle of 45° compared to the simulations. Although the overall accordance is satisfying, higher deviations are detected compared to the results with system 1. Mainly, an overestimated temperature as well as a faster temperature rise can be recognized by the simulation model. The mean deviation between measurement and simulation is in the range of ±10 K. In Table 4 the Root-mean square errors (1) are summarized for all measured layer and gap temperatures at each slat position and each system. Systematically, the lowest deviations are at the layers on the outer and inner side of the glazing system (OT10/OT16). And generally, highest deviations are reached in both systems for closed blind positions.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{meas} - y_{sim})^2} \qquad (1)$$

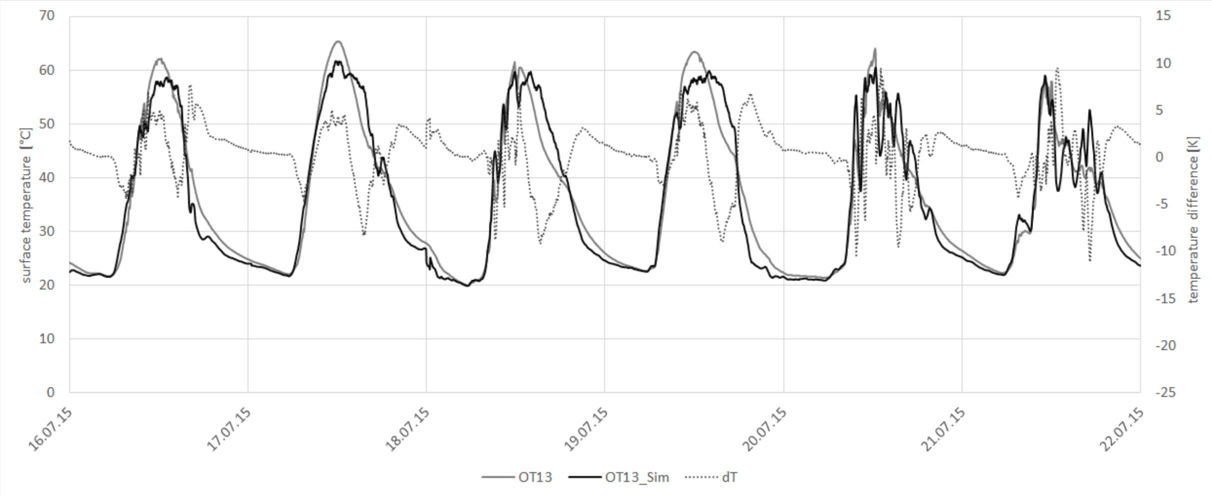

Fig. 8 – Blind temperature, System 1 - 45° slat angle

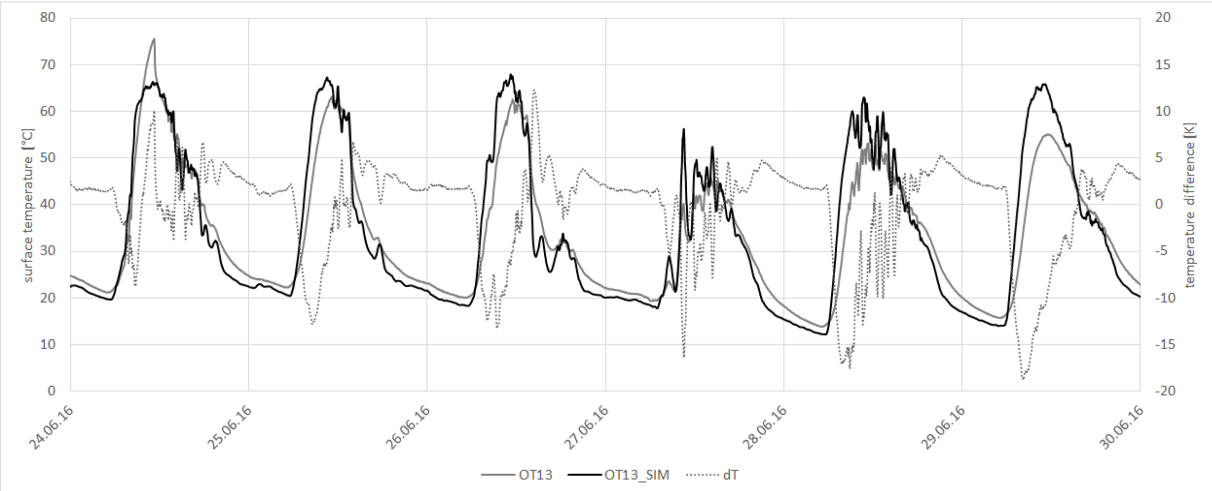

Fig. 9 – Blind temperature, System 2 - 0° slat angle

Table 4 – RMSE for temperature differences (in K) measured vs. simulated values (level 1)

SYS1	dT_OT10 [K]	dT_LT12 [K]	dT_OT12 [K]	dT_OT13 [K]	dT_LT14 [K]	dT_OT15 [K]	dT_OT16 [K]
00deg	2.575	4.187	3.249	3.111	3.981	4.542	2.572
45deg	1.889	2.806	2.323	2.277	2.682	3.137	1.169
85deg	4.433	5.765	5.455	5.432	5.387	6.524	1.694
SYS2							
00deg	4.702	5.149	6.243	6.248	6.027	6.820	1.322
45deg	3.112	3.794	4.962	5.266	6.223	6.844	0.943
80deg	2.594	3.793	10.327	10.79	9.902	12.395	3.251

6. Conclusions

By collecting long-term measurement data for two different façade systems, an extensive proof of the model validity of the recently implemented BSDF/ISO-model in TRNSYS Type56 could be shown. The results are very satisfying in general. Deviations between measurement and modelling are shown especially for peak values. Reasons for this can be either through model simplifications done by ISO 15099 (convective model, layer emissivity) or either by a limited resolution for the optical modelling by the BSDF data based on Klems resolution. Especially for system 2 (specular blind surface) this aspect could be critical.

In the overall results by the RMSE-analyse, the highest deviations are mentioned for closed blind conditions that are not satisfying. In this case, an individual analysis for the measured values on level 3 (bottom) showed much better accordance compared to level 1. A strong stack effect by temperature layering could be obtained, which is not sufficiently represented in the modelling.

In general, neglecting the thermal mass of the single glazing could show a significant influence on the modelled layer temperatures. With an increasing layer number (from outside to inside) an increasing time shift of approx. 0,5-1 hour between measured and simulated values occurred. In case of future trends in modelling glazing systems up to 4 panes including a shading layer, this aspect gains significant relevance. A model adoption towards including the thermal mass is recommended.

Based on these conclusions, further in-deep analysis of the model will be done by static measurements in a g-value test chamber as well as dynamic measurements with a newly developed measuring method for in-situ g-value measurements. Beside the gained validation results, this work successfully represents the full workflow, starting from the manufacturers' information, the use of powerful (partly free) tools (genBSDF, WINDOW7, IGDB) to generate the needed simulation data and built up of the model for simulating complex fenestrations systems.

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