CFS Model Improvement based on Measured Data of a 1:1 Scale Test Mock-up

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Abstract

Comparisons of measurements at a 1:1 scale mock-up with detailed thermal simulation offer a great opportunity for model evaluation.

Due to the composition of the investigated glazing system (8 mm + 8 mm PVB laminated glass, solar protection coating, 5 mm glass and 8 mm glass) the authors extended the existing complex fenestration model (CFS) of the multizone building model of TRNSYS by adding heat capacity for glass layers.

Simulation results with and without glass capacity consideration are compared to measurements at a 1:1 scale facade mock-up.

The results show that the consideration of heat capacity of the glass layers improves the match to measured data significantly. The extended model resolves issues of high peak temperatures and a shift in time of occurrence. The simulation results of the improved CFS model match closely to the measurements of the mock-up.

Introduction

Thermal building performance simulations are used more frequently than ever by engineers and architects to evaluate highly glazed buildings. Comparisons of measurements at a 1:1 scale mock-up with detailed thermal simulation offer a great opportunity for model evaluation.

For a current ongoing high-rise project, different facade concepts of solar protection glazing with internal screens combined with displacement ventilation have been investigated. Detailed measurements were performed at 1:1 scale test mock-up of a typical office at a test building facility under real weather conditions.

Measurements of the highly glazed facade under investigation were compared to detailed thermal simulation with TRNSYS (Klein, 2018) utilizing a complex fenestration model (CFS) (Hiller, 2013).

First results indicated that a temporal misalignment may be caused by a lack of thermal mass in the modelled glazing system. The CFS model of TRNSYS is based on ISO 15099 (ISO, 2003). The ISO 15099 (ISO, 2003) describes a detailed thermal model, but doesn't take into account the heat capacity of the glass panes. For many applications this is a valid assumption, but for multi-pane glazing systems with a large total glass thickness and solar

protection coating the capacity may have considerable impact on the resulting surface temperatures since glass has a thermal density in the range of concrete ($\rho_{\text{glass}} = 2500 \text{ kg/m}^3$) and a heat capacity of approx. 0.8 kJ/(kg K) .

Due to the composition of the investigated glazing system (8 mm + 8 mm PVB laminated glass, solar protection coating, 5 mm glass and 8 mm glass) the authors decided to further investigate the impact of the heat capacity. Therefore, the existing complex fenestration model was extended to account for the heat capacity of glass layers.

For better understanding a step response test was performed first. In a second step the simulation results with and without heat capacity consideration were compared to measurements of the mock-up. The measurements include a base case with sun protection glazing only as well as a test sequence including internal screen.

Façade Mock-Up

The Modular Test Facility for Energy and Indoor Environments (VERU) is located on the Holzkirchen test site of Fraunhofer Institute for Building Physics IBP, Germany enables practice-oriented tests on a 1:1 scale under natural weather conditions. The geographical coordinates of the site are 47.88° northern latitude and 11.73° eastern longitude, and it is 690 m above sea level.

Figure 1: Picture of test facility with the investigated façade.

The test facility is a multi-storey building. The test cell is box shaped with a width of 3.75 m, a depth of 6.14 m and

a clear height = 3 m near the façade and up to 3.25 m in the rear.

The investigated façade was mounted at the south side of the left test cell, 2nd level of the as shown in Figure 1. The façade is divided into two modules (2.56 m x 2.96 m and 0.79 m x 2.96 m).

The glazing system consists of a triple pane, sun protection glazing ($T_v = 0.53$, $T_e = 0.22$, $U_g = 0.5 \text{ W/m}^2\text{K}$, $g = 0.25$) and an optional internal white screen (4% opening factor, $T_v = 0.48$, $T_e = 0.46$, $a_e = 0.40$). The composition of the glazing without screen is presented in Table 1. The distance between the screen and the inner glazing layer is 21 cm. There are no air gaps at the screen side and bottom edges.

Table 1: Glazing system (from outside to inside).

number	BE	name	thickness [mm]
1		Planibel Clear	8.00
2		PVB-Folie	0.76
3		Planibel Clearlite	8.00
4	2	ipasol ultraselect 62/29 ($\epsilon_n = 1 \%$)	
5		90% Argon	16.00
6		Optifloat	5.00
7		90 % Argon	16.00
8	5	iplus Top 1.1 T ($\epsilon_n = 3 \%$)	
9		Planibel Clearlite	8.00
			61.76

Table 2 provides an overview of the opaque surface constructions. The test cell has installed three cooling sails (each 2,00 m x 1,15 m) near the façade and thermally activated slab systems in the rear (1 element with 3,75 m x 1,90 m and 2 elements with 3,75 m x 0,70 m). Neither system was activated during the test periods.

The air temperature of the test cell was kept at a constant minimum temperature by an electric heater.

Fresh Air with a constant air flow rate of approx. 105 m³/h at 20 °C was provided by underfloor convectors near the façade. For these test sequences the exhaust air is extracted at ceiling level close to façade (not from the cavity between glazing and screen).

The following measurements are used as boundary conditions for the simulation at a three-minute time steps:

- Horizontal global radiation
- Global radiation on the south facade
- Downward heat radiation on a horizontal plane
- External air temperature
- Wind velocity
- Wind direction
- Relative humidity
- Surface temperatures of test cell surfaces of the walls and ceiling (3 position for the cooling sails and 3 position for the thermally activated slab)
- Air temperature of the raised floor
- Air temperature in test cell measured at a distance of 2 m from the façade at different heights (0.6 m, 1.1 m and 1.7 m)

Table 2: opaque surface constructions.

component	construction	thickness [mm]
west façade	glazing plastered externally with opaque, pale foil	
	airspace	225
	insulation (mineral wool)	60
	plasterboard	12.5
	air gap	80
adjacent wall east	plasterboard	12.5
	plasterboard	25
	insulation (mineral wool)	160
adjacent wall north	plasterboard	25
	insulation (mineral wool)	160
	plasterboard	25
access door	timber (glue-laminated) with viewing window	50
floor	carpet (floor tiles)	6
	raised floor	38
	air space	260
	concrete	250
ceilling	floor screed	55
	insulation (EPS)	30
	concrete with component activation	250
	or prefabricated concrete element with component activation	125
	area with cooling sails and additional insulation	50

For comparison to simulation results the following measurements are used:

- Outside surface temperature of the main glazing (at a height 1.6 m)
- Inside surface temperature of the main glazing (at a height 16 m)
- Cavity air temperature of the main glazing (at a height of 0.95 m, 1.6 m, 2.25 m)
- Screen temperature of the main glazing

Additional measurements of glazing and screen surfaces have been taken at different heights. The sensors for the glazing temperature measurements were mounted unshielded with thermally conductive paste.

The following test cases were measured.

- Case 1: glazing without screen
- Case 2 :glazing with internal screen

Each test sequence includes cloudy conditions with mainly diffuse radiation and clear sky conditions with high solar radiation.

Modelling

For the thermal simulation the focus was on the detailed modelling of the glazing system.

Glazing system

Thermal models based on ISO 15099 (ISO, 2003) are commonly used for detailed glazing modelling. Such models are available in building performance simulation

software like TRNSYS (Hiller, 2014) and EnergyPlus (US DOE, 2018) as well as in computer programs for calculating total window thermal performance indices like Window (LBNL, 2018).

The ISO 15099 model is based on the heat flow balances of each layer. The layers are merely differentiated by air-impermeable (e.g. glazing) and permeable (e.g. shading elements) layers. Adjacent gaps or a gap and the external/internal air are aerodynamically connected due to the opening areas of shading elements (see Figure 2)

Figure 2: Opening areas of a shading element (ISO, 2003)

Figure 3 shows the heat flow for each layer of the glazing system. If the direction of the heat flow is a priori unknown, it is depicted from right to left.

Figure 3: Thermal exchanges in the glazing system (Schöttl, 2013)

The used variables are described in the following paragraph:

The **radiation flow** S_i is caused by the solar radiation absorption of each particular layer. It is assumed that the radiation flow is absorbed evenly over the pane thickness t_i .

The **radiosities** $J_{f,i}$ and $J_{b,i}$ include the fraction emitted by the boundary surface as well as those transmitted and reflected.

$$J_{f,i} = \overbrace{\epsilon_{f,i} \sigma T_{f,i}^4}^{EM} + \tau_{I R,b,i} J_{f,i+1} + r_{I R,f,i} J_{b,i-1} \quad (1)$$

$$J_{b,i} = \epsilon_{b,i} \sigma T_{b,i}^4 + \tau_{I R,f,i} J_{b,i-1} + r_{I R,b,i} J_{f,i-1} \quad (2)$$

By means of **heat conduction** a heat flow emerges and flows through the solid layer with the thickness t_i and thermal conductivity λ_i .

The **convective heat transfer** h_{cv} causes the flows $\dot{q}_{cf,i}$ und $\dot{q}_{cb,i}$. They flow from the solid layer to gas and vice versa.

When the gas gap is ventilated, a **heat flow** $\dot{q}_{ven}$, which influences the gas temperature, exists. The ventilation may be thermally or mechanically induced. The algorithm for thermally-driven ventilation is given by ISO 15099.

The following system of equations results:

Front i:

$$0 = -\frac{\lambda_i}{d_i} (T_{f,i} - T_{b,i}) + \frac{S_i}{2} - h_{cv,f,i} (T_{f,i} - T_{g,i-1}) + J_{b,i-1} - J_{f,i} \quad (3)$$

Back i:

$$0 = -\frac{\lambda_i}{d_i} (T_{b,i} - T_{f,i}) + \frac{S_i}{2} - h_{cv,b,i} (T_{b,i} - T_{g,i}) + J_{f,i+1} - J_{b,i} \quad (4)$$

Gas layer i:

$$0 = h_{cv,f,i} (T_{f,i+1} - T_{g,i}) - h_{cv,b,i} (T_{g,i} - T_{b,i}) + h_{ven} (T_{g,in,i} - T_{g,i}) \quad (5)$$

As shown by the above equations, the original ISO 15099 model neglects the heat capacity of the glazing system. This assumption is valid for most applications.

For investigating the effect of the thermal mass on the resulting temperatures of the installed glazing system the existing complex fenestration model of TRNSYS (Hiller, 2014) was extended.

Equation (3) and (4) were modified by adding a capacity term to the front and back surface node of a layer:

Front i:

$$0 = -\frac{\lambda_i}{d_i} (T_{f,i} - T_{b,i}) + \frac{S_i}{2} - h_{cv,f,i} (T_{f,i} - T_{g,i-1}) + J_{b,i-1} - J_{f,i} - \frac{\kappa_i}{2 \Delta t} (T_{f,i} - T_{f,i,t-1}) \quad (6)$$

Back i:

$$0 = -\frac{\lambda_i}{d_i} (T_{b,i} - T_{f,i}) + \frac{S_i}{2} - h_{cv,b,i} (T_{b,i} - T_{g,i}) + J_{f,i+1} - J_{b,i} - \frac{\kappa_i}{2 \Delta t} (T_{b,i} - T_{b,i,t-1}) \quad (7)$$

where κ_i is the area related heat capacity of layer i, Δt is the simulation time step, $T_{f,i,t-1}$ and $T_{b,i,t-1}$ are the node temperatures of layer i from the previous time step.

Step response test

For better understanding of the heat capacity effect on the resulting temperature a step response test was performed.

Table 3: Boundary conditions of step response test

	Winter	Summer
Air temperature, exterior	-18 °C	32 °C
Radiation temp., exterior	-18 °C	32 °C
Emissivity, exterior	1	1
Wind velocity, exterior	5.5 m/s	2.8 m/s
Air temperature, interior	21 °C	24 °C
Radiation temp., interior	21 °C	24 °C
Emissivity, interior	1	1
Solar direct radiation	0 W/m ²	783 W/m ²

Therefore, a 3D zone with one airnode including the mock-up façade was defined in the multizone building model of TRNSYS. The boundary conditions inside and outside were switched from winter conditions to summer conditions (see Table 3). The simulation time step was 0.1 hours.

Mock-up

The test cell was modelled by the multizone building model of TRNSYS as a 3D zone with one airnode with the south façade as the only external surface.

The glazing system was modelled by the previously described model. Information regarding the composition and properties of layers and gaps of the glazing system were generated from WINDOW 7- outputs and provided by an external file to the model.

The measured interior surface temperatures of the walls and ceiling were imposed on the model surfaces. For the cooling sails as well as for the thermally activated slab mean values of the measured temperatures were applied. Since the interior floor surface temperature wasn't measured, the raised floor was modelled as constructed with the measured air temperature as boundary condition.

For calculation of the exterior surface convective heat transfer a modified MoWiTT algorithm is used. The algorithm is based on measured data for glass surfaces from Lawrence Berkeley National Laboratory's Mobile Window Thermal Test facility (Yazdanian and Klems, 1994). The modified algorithm accounts for local-height wind speed, surface orientation and surface roughness (ANSI/ASHRAE, 2017). The exterior longwave exchange with the sky and the ground surface is calculated explicitly.

The interior surface convective heat transfer coefficient was calculated by the internal model of the multi-zone building model depending on surface orientation and difference between the interior surface and air temperature. For modelling the interior surface longwave radiation exchange the detailed mode based on 3D geometry and surface emissivity was applied.

The airnode temperature of the zone was set to the mean value of the measured air temperatures of the test cell.

The measured weather data of the mock-up was directly used as input for the building model. Since only the global radiation on the south façade was measured, the distribution between direct and diffuse was calculated by a radiation processor according to the Perez-Model (Perez et al., 1990). The ground surface temperature wasn't measured and was assumed to be equal to the exterior air temperature. The sky temperature was derived from the measured downward heat radiation on the horizontal.

Results and discussion

Step response test

Figure 4 - Figure 5 show the resulting mean temperatures of the glazing layers modelled with and without capacity.

The layers are numbered from outside to inside. The screen has no capacity associated.

Figure 4: Step response test, glazing system (no screen) without and with glass capacity.

Figure 5: Step response test, glazing system including screen with and without glass capacity.

Until hour 3 steady state winter conditions are applied resulting in constant layer temperatures for both models. When switching from winter to summer conditions the layer temperatures modelled without glass layer capacity rise instantaneously in the next time step to steady state summer conditions. Steady state layer temperatures of the glazing systems have been compared to WINDOW 7.4 result. The deviations are negligibly small.

Table 4: Response characteristic of glazing system without screen considering glass capacity

	63% ΔT	86% ΔT	95% ΔT
Tglzlay1_cap	0.5 h	1.05 h	1.65 h
Tglzlay2_cap	1.65 h	2.85 h	4.1 h
Tglzlay3_cap	1.5 h	2.85 h	4.15h

Table 5: Response characteristic of glazing system with screen considering glass capacity

	63% ΔT	86% ΔT	95% ΔT
Tglzlay1_cap	0.5 h	1.05 h	1.7 h
Tglzlay2_cap	1.75 h	3.05 h	4.4 h
Tglzlay3_cap	1.5 h	2.6 h	3.9 h
Tglzlay4_cap	0.65 h	1.8 h	2.95 h

Table 4 and Table 5 present the response characteristic of the glazing systems considering glass capacity with and without the screen, respectively. The exterior glass layer (Tglzlay1_cap) shows the largest temperature step due to solar absorption and the step increase of exterior temperature. The largest delay is encountered for the 2nd layer (Tglzlay2_cap) which has the lowest heat capacity but is influenced by the adjacent layers.

Mock-up Case 1: glazing without screen

In the following section, the results of the test period without screen for 3 days from January 15 – 17, 2019 for the mock-up are presented.

As shown in Figure 6, the first day was cloudy with low diffuse incident radiation on the south façade. The next two days show clear sky conditions with high incident solar radiation of up to 950 W/m² on the facade. The wind speed in this period varies from velocities around 6 m/s to very low velocities below 1 m/s on January 16. The measured ambient air (Tairamb_m) and sky temperature (Tsky_m) is included in Figure 7 and Figure 9.

Figure 6: Incident Solar Radiation on the south façade and wind speed at 10 m

The measured and simulated surfaces temperature of the glazing system without glass capacity are presented in Figure 7 and Figure 8. Figure 9 and Figure 10 show the results considering the heat capacity of the glass layers.

Figure 7: Comparison of exterior surface temperature of the glazing without glass capacity

During day time with high solar radiation the resulting surface temperature modelled without glass layer capacity shows a significant time shift compared to the measured results. The time shift for the exterior surface (Tglzlay1_s) is moderate with approx. 0.6 h, whereas a

larger shift of approx. 1.6 h is seen for the interior surface (Tglzlay3_s). In addition, the simulated temperatures show much higher peaks on January 17 where solar radiation conditions change rapidly.

Figure 8: Comparison of interior surface temperature of the glazing without glass capacity

As presented in Figure 9 and Figure 10, the consideration of the heat capacity of the glass layers in the simulation model improve the match to the measured data during day time significantly. The simulated curves show the same trend as the measured ones without time delay. In addition, the high temperature peaks caused by fluctuating radiation are resolved.

Figure 9: Comparison of the exterior surface temperature of the glazing considering glassing capacity

Figure 10: Comparison of interior surface temperature of the glazing considering glass capacity

The exterior surface temperature closely matches with the measurements during cloudy conditions. For clear sky conditions a deviation of max. - 3 K is observed. By considering the root-mean-square error (RMSE) of the exterior surface temperature is reduced from 2.61 to 1.41 during times without incident direct solar radiation.

During day time with high incident solar radiation large temperature difference between the exterior surface and the exterior boundary temperatures (36.8 K related to ambient air temperature and 59.8 K to the sky temperature on January 16) occur. During this time the resulting exterior surface temperature highly depends on the exterior heat transfer coefficients. Small differences of the modelled heat transfer coefficients have a larger impact on the resulting exterior surface temperature. With respect to this, it can be concluded that the modelled exterior heat transfer coefficients are representative of the real conditions. For sunny conditions RMSE of the exterior surface temperature is reduced from 8.05 to 2.91.

The interior surface temperature shows good agreement with measurements. For temperature peaks deviation of approx. -0.5 K is encountered. The RMSE is reduced from 2.74 to 0.51.

For cloudy conditions when the test cell was heated to minimum air temperature the measured and simulated interior surface temperature show the same trend but with an offset of approx. 0.7 (moderate sky temperatures) to 1.3 K (low sky temperatures) The offset can be explained by the radiative part of the heater elements which couldn't be considered in the simulation due to a lack of measured electrical heating consumption. This explanation is supported by additional measurements under cloudy conditions from December 23 – 25, 2018 where the heater elements were switched off temporarily for several hours due to a power failure. Without heating the deviation between measured and simulated interior surface temperature decreases to a neglectable range of max. 0.2 K. (see Figure 11)

Figure 11: Comparison of interior surface temperature of the glazing considering glass capacities with heating failure

Case 2: Mock-up – glazing with internal screen, exhaust air from room side

In contrast to the previous test sequence, the interior screen is now mounted and closed permanently. The ventilation of the cavity between glass and screen is thermally-driven. The 3-day test period took place from February 12 – 14, 2019.

As shown in Figure 12 the weather conditions are comparable to the previous test period. The first day was

cloudy with low incident diffuse radiation on the south façade. The next two days show clear sky conditions with high incident solar radiation of up to 960 W/m² on the facade. The wind speed in this period varies from velocities around 5 m/s for the first day to lower velocities of 1 - 2 m/s for the other days. The measured ambient air and sky temperatures are included in Figure 13 and Figure 17.

The measured and simulated temperature of the glazing system without glass layer capacity are presented in Figure 13 - Figure 16. Figure 17 - Figure 20 show the results considering the heat capacity of glass layers.

Figure 12: Solar Radiation data on the south façade and wind speed at 10 m height

As expected from the previous results the simulated temperatures without capacity show a significant time shift compared to the measurements and more fluctuation. The extended model considering the heat capacity of the glass layers improves the match to the measured data significantly.

Similar to the presented result of Case 1, an offset of the simulated inner surface temperature (here the screen) during heating conditions is encountered (see Figure 20). As mentioned before, the offset is caused by the radiative part of the heater elements which wasn't considered in the simulation model. The peak screen temperature deviation is reduced by considering glass layer capacity from 2K to 1.2 K.

The interior glazing surface temperature is no longer affected by longwave radiation exchange with the heater elements resulting in a very good agreement for the whole test sequence (see Figure 18).

Figure 19 shows the simulated cavity outlet temperature as well as measured cavity air temperatures at 0.95 and 2.25 m, respectively. During sunny conditions the cavity air temperature is higher than the air temperature of the test cell resulting in air flow from bottom to top. The simulated outlet temperature is in good agreement with the air temperature measured at 2.25 m height. During heating conditions, a reversed flow from top to bottom occurs because the cavity temperature is lower than the air temperature of the test cell. For this case, the simulated outlet temperature is in good agreement with the air temperature measured at 0.95 m height.

Figure 13: Comparison of the exterior surface temperature of the glazing without glass capacities

Figure 17: Comparison of the exterior surface temperature of the glazing considering glass capacities

Figure 14: Comparison of interior temperature of the glazing without glass capacities

Figure 18: Comparison of interior temperature of the glazing considering glass capacities

Figure 15: Comparison of simulated cavity outlet temperature without glass capacities and measured cavity temperatures at different height

Figure 19: Comparison of simulated cavity outlet temperature considering glass capacities and measured cavity temperatures at different height

Figure 16: Comparison of the screen temperature without glass capacities

Figure 20: Comparison of the screen temperature considering glass capacities

In addition, the benefit of considering the heat capacity of the glass layers is shown by looking at the resulting RSME during periods without and with incident solar radiation, respectively (see Table 6 and Table 7).

Table 6: RSME of surface temperatures during periods without incident direct solar radiation

	without capacity	with capacity
Tglzlay1	5.13	2.09
Tglzlay3	3.14	0.29
Tglzgap3	1.48	0.35
Tglzlay4	1.22	0.70

Table 7: RSME of surface temperatures during periods with incident direct solar radiation

	without capacity	with capacity
Tglzlay1	7.89	2.39
Tglzlay3	4.52	0.54
Tglzgap3	2.02	0.73
Tglzlay4	1.58	0.75

Conclusion

This paper has presented a comparison of detailed glazing system modelling to measured data from a 1:1 scale test mock-up.

Due to the composition of the investigated glazing system (8 mm + 8 mm PVB laminated glass, solar protection coating, 5 mm glass and 8 mm glass) the authors extended the existing complex fenestration model (CFS) of the multizone building model of TRNSYS by adding heat capacity for glass layers.

The results show that the consideration of heat capacity of the glass layers improves consistency with the measured data significantly. The previously noted discrepancies regarding high peak temperatures and time of occurrence, especially during periods with rapidly changing solar radiation, are resolved.

For the two test cases, sun protection glazing with and without internal screen, the simulation results of the

improved CFS model are in good agreement to measurements. In addition, it can be concluded that the modelled exterior heat transfer coefficients are representative of the real conditions.

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