Implementation and Calibration of a Model to Treat Naturally Ventilated Complex Fenestration Systems in TRNSYS

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Abstract

Adaptive façade systems offer the opportunity to improve building performance and user experience with their ability to adapt the façade configuration to the dynamic variability of the external environment. Nevertheless, the correct deployment of adaptive systems in real buildings is highly dependent on the ability to predict their performance. This is especially relevant in the case of Complex Fenestration Systems (CFS), which are characterized by a complex behavior both from a thermal and daylighting perspective. Often, such CFS are combined with airflow movement when the façade cavity is either mechanically or naturally ventilated, making the performance even more difficult to be characterized. The possibility to use building performance simulation tools to simulate the behavior of these systems integrated in a whole building is central for the proper use and the penetration on the market of these systems.

In this framework, a naturally ventilated window with integrated venetian blinds was modeled in TRNSYS and compared with a FEM-based 2D detailed model, developed in COMSOL Multiphysics. Type56_CFS solves thermal calculation and uses the Bidirectional Scattering Distribution Function for describing optical properties of the façade. This model requires the inlet mass flow rate, which was assessed thanks to an ad-hoc implementation of ISO 15099. The numerical modeling of the coupled heat transfer and fluid flow with COMSOL allowed the TRNSYS model to be calibrated.

The calibration was carried out by increasing the model complexity, focusing on the inlet ventilation flow rate parameter: (a) firstly, it was provided as an input to the Type56_CFS from the FEM-based simulation and then (b) it was calculated by the ISO 15099 internal model and provided to the Type56_CFS. Using this methodology, it was possible to compare the ability of TRNSYS to simulate the thermal behavior of the naturally ventilated cavity against a FEM-based benchmark. Results show a difference of 5 % after the fine tuning of all TRNSYS-related parameters (40 % as un-calibrated starting value).

1. Introduction

Complex Fenestration Systems (CFS) can provide a valuable solution to lower the building energy needs by optimizing solar gains during winter, limiting them during the cooling season and reducing artificial lighting (Huckemann et al., 2010; Pomponi et al., 2016). In order to correctly implement these solutions, it is of crucial importance to predict their thermal and day-light behavior.

To this purpose, two main approaches can be used: on the one hand, FEM methods can be adopted to determine in a detailed way its thermal behavior, since all the system components and the relative thermo-physical properties are taken into account, along with the underlying thermo-physical phenomena (Dama et al., 2017; Li et al., 2017; Wang et al., 2016). As Jankovic and Goia (2021) stated, computational fluid dynamics methods are the most suitable tools for solving problems related to these systems. On the other hand, Building Energy Simulation (BES) tools implement simplified methodologies for taking into account the effect of such complex systems on the building scale and, in the case of open cavity fenestration systems, they are typically designed for modeling mechanically ventilated ones. The unavoidable approximations related

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to the impossibility of fully considering the geometries and the detailed physical phenomena, however, strongly limit the modeling possibilities, especially when unconventional complex systems are considered. Catto Lucchino et al. (2021) used different BES tools to predict the behavior of a mechanically ventilated Double Skin Façade, and compared the results with measured data; the conclusions state that these tools can be acceptable for predicting an overall performance over a long period, but for short-term performance assessment the error is too large.

In this study, a CFS characterized by a naturally ventilated cavity with an integrated venetian blind was considered. Through a coupled heat transfer and fluid flow simulation with FEM-based calculation software, it is possible to fully capture the fenestration behavior at system scale, but great limitations are found if its impact on the building scale needs to be assessed. These limitations are particularly related to natural ventilation, which is always harder to predict compared with the mechanical ventilation (Wang et al., 2019). This paper hence aims at identifying the natural ventilation modeling limitations for CFS by comparing two calculation approaches (namely, concentrated-parameters and FEM-based models). To answer this research question, a custom simulation setup was built in TRNSYS 18 with the aim of modeling the naturally ventilated window with integrated venetian blinds and assessing its impact on the building scale. To allow this, a FEM-based 2D detailed model was developed in COMSOL Multiphysics with the purpose of obtaining the necessary data to support and calibrate the implementation of the proposed TRNSYS simulation setup.

2. Methodology

2.1 Case Study

In this study, a CFS consisting of a naturally ventilated window with integrated venetian blinds was studied. Fig. 1 shows how the window cavity is in direct connection with the external environment at the bottom and at the top part. A peculiarity is present in the shape of the external openings, which are not continuous along the fenestration width, but interrupted by solid (closed) parts, as shown in Fig. 1. Additionally, the external openings are covered by a grille characterized by the ratio of blocked area to total area of 1/5. Furthermore, there is a second (internal) vent that is continuous along the fenestration width and characterized by a depth of 5 mm.

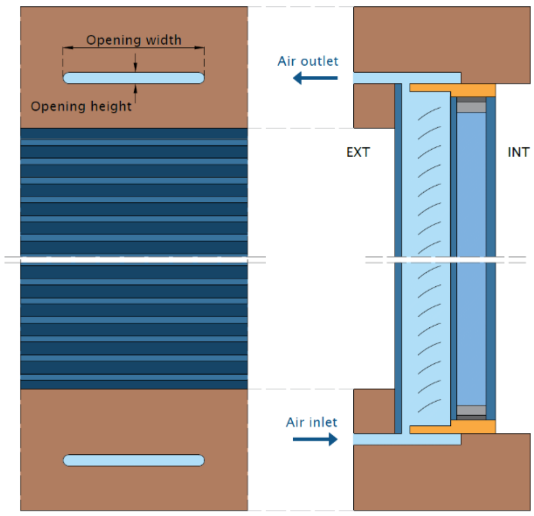

Fig. 1 – Scheme of the considered CFS: front view of a portion of the CFS (left) and vertical cross section (right)

The integrated venetian blind has a direct impact on the airflow and, therefore, on the cavity air temperature in terms of blind type and angles of the slats. In this study, the venetian blind was deployed with slat angles of 0°, 30° and 75° with respect to the horizontal plane. The external cavity (cavity 1) is composed of air, as it is in direct contact with the external environment, while the internal cavity (cavity 2) is filled with a gas mixture of 90 % argon and 10 % air. The external (1) and central (2) glasses are made of single float glass panes of 4mm, while the internal glass (3) is laminated and composed of two float glass panes of 3mm each and one PVB layer. On face 5 (exterior side of the interior glass pane) a low-emissivity coating is placed with an emissivity of 0.013. The geometrical properties of the CFS are listed in Table 1, while the thermal characteristics are reported in Table 2.

Table 1 – *CFS* geometric parameters

Symbol	Parameter	Value
dglass1-2	Glass 1-2 thickness	4 mm
dgap1	Cavity 1 width	30 mm
dgap2	Cavity 2 width	18 mm
dglass3	Glass 3 thickness	6 mm
w	Blind width	16 mm
α	Blind tilt	0°/30°/75°
H	Cavity height	1.33 m
open_w	Opening width	80mm
open_h	Opening height	7mm

Table 2 – *CFS* thermal parameters

Symbol	Unit	Blind	Glass1-2	Glass3	Frame
λ	W/m/K	100	1.0	0.65	0.12
c_p	J/kg/K	900	820	820	2700
ϱ	kg/m³	2700	2500	2500	532
ε_f	-	0.212	0.84	0.013	0.84
ε_b	-	0.489	0.84	0.84	0.84

2.2 Simulation workflow

The workflows adopted in the different modeling and simulation approaches of the CFS (FEM-based at system scale and using TRNSYS at building scale) are described in this chapter. The system scale simulation allowed an assessment of the system's performance in detail and temperature and airflow data to be gathered, later used to support the calibration of the TRNSYS model.

2.2.1 System scale simulation approach

The FEM-based software COMSOL Multiphysics (COMSOL n.d.) was used to compute the coupled heat transfer and fluid flow of the analysed CFS. To simplify the model and reduce computation time, the geometry of the CFS was reduced to a vertical cross section and modeled as a bi-dimensional domain. This assumption was supported by the statement of Pasut and De Carli (2012) describing that the 3D modeling of a fenestration system does not provide a substantial improvement in the results, considering the additional complexity and computation time. The discretization of the domain occurred through the creation of a calculation grid (mesh). This latter was done dividing the geometry into various domains so that, according to the geometric and material characteristics, different types and sizes of the mesh could be adopted. To ensure that the solution is independent from the calculation grid, a mesh refinement study was carried out , and the thermal transmittance was used as control parameter. The final mesh is reported in Fig. 2.

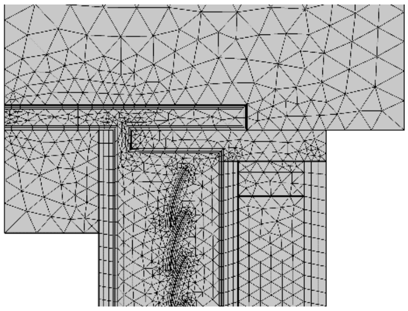

Fig. 2 – Final mesh of the Complex Fenestration System

The modeling of the short-wave radiation exchange due to solar irradiance was done outside the FEM model through a detailed optical calculation using Radiance (Ward, 1994). For each shading configuration, the Bidirectional Scattering Distribution Function (BSDF) was calculated and the solar absorption data for each glass pane and the shading system were derived. The share of incident solar radiation absorbed by each layer of the fenestration system was finally assigned as heat source to single domains within the FEM-based dynamic simulation (Demanega et al., 2020).

To model the natural ventilation through the open window cavity and the top and bottom vents, two additional domains representing the external ambient were added to the model. A relative pressure of 0 Pa was assigned to the top domain's boundaries and of $\frac{1}{2}\rho u^2$ to the bottom ones.

The presence of the grille on the vents was modeled as a pressure drop for a squared mesh described by the equation 1 (COMSOL n.d.), with a solidity σ_s (ratio of blocked area to total area of the screen) equal to 1/5.

$$K = 0.98\,((1-\sigma_s)^{-2}-1)^{1.09} \quad (1)$$

To account for the discontinuity of the external vertical opening, which is interrupted by solid (closed) parts along the fenestration width, this non-homogeneity was described analytically in the bi-dimensional FEM model through a localized pressure drop equation of the type $\Delta p = f(u)$, which was determined by means of a separate FEM CFD 3D model focussed only on the ventilation openings.
The thermal boundary conditions were assigned in terms of convective and radiative heat flux on the internal and external glazing surfaces, while adiabatic conditions were assumed for the top and bottom boundaries. The simulation was run in a stationary regime and considered converged when the relative residuals of the continuity, momentum and energy equations were less than 10e-4.

2.2.2 Building scale simulation approach

TRNSYS 18 was used as building dynamic energy simulation software to assess the impact of the CFS on the building scale. A single thermal zone with one window was modeled using the new version of the multi-zone building model Type 56 CFS. This inbuilt model enables a detailed CFS thermal simulation according to ISO 15099:2003 and uses the BSDF for describing the façade optical properties in the solar and visual band. This Type has been mainly meant to model mechanically ventilated gaps; indeed, it requires as input the inlet mass flow rate (together with its temperature), which is easily available from fan datasheets; however, in the case of naturally ventilated windows, this data is not known a priori because it is highly dependent on the cavity geometry and boundary conditions. For this reason, a Python-based script was implemented through TRNSYS Type 169, which calculated the inlet mass flow rate according to the ISO 15099. The air moves inside the cavity due to the stack effect, thus the velocity of the air gap depends on the driving pressure difference and the resistance of the openings. The airflow in the cavity is modeled as a pipe flow and the driving force of the flow is set equal to the total pressure loss, which takes into account Bernoulli's pressure loss, steady laminar flow and pressure loss due to the inlet and outlet openings. The resulting model exhibits an interdependence between the air gap temperature and velocity and consequently an iterative calculation is performed until the relative convergence limit is less than 1 %.

2.2.3 Model calibration

Given the absence of measured data, the TRNSYS model was calibrated against the FEM one. To support this calibration, parametric simulations were performed with the FEM model considering all combinations of external air temperature ($T_{air,ext}$), internal air temperature ($T_{air,int}$) and solar irradiance (I_{sol}) listed in Table 3.

Table 3 – Boundary conditions for parametric simulations

$T_{air,ext}$ (°C)	0, 5, 10, 15, 25, 30, 35
$T_{air,int}$ (°C)	20, 24, 28
I_{sol} (W/m²)	0, 250, 500, 750, 1000

COMSOL Multiphysics and TRNSYS 18 have two different approaches to simulate the thermal behavior of CFS. Therefore, to minimize these differences and to set the same boundary conditions, the following assumptions were used in the TRNSYS model: a single-zone "shoe-box" model was used as thermal zone, the surface temperatures of the walls were set equal to the indoor temperature and the view factor to the sky of the façade was set to 0.5 (as in the FEM-model).
To achieve steady-state conditions for every combination of the boundary conditions (as listed in Table 3), simulations were run for 100 hours while keeping fixed the values of $T_{air,ext}$, $T_{air,int}$ and I_{sol}. Results correspondent to the last timestep of each simulation were considered as the steady-state ones.
The ad-hoc TRNSYS Type was carried out by increasing the model complexity step by step, focusing on the inlet ventilation flow rate and the total heat flux.
In a first step, the mass flow rate resulting from the thermo-fluid dynamic simulation was provided as input to the TRNSYS type in order to tune the Type 56 CFS parameters and, in a second step, it was calculated by the Python-based Type 169 and provided as input to the TRNSYS building model. Comparing the outcomes of the two models at component level, it was possible to calibrate the natural flow rate Type, particularly focusing on the tuning

of the pressure loss factor along the window cavity, which takes into account the pressure losses caused by the ventilation openings (inlet and outlet), the squared mesh grille and the integrated venetian blinds. The ISO 15099 describes the pressure loss in the inlet and outlet openings through equation 2 and 3, and, in case of zero lateral opening area and equal top and bottom opening area, equation 4.

$$\Delta P_Z = \frac{1}{2}\rho v^2 (Z_{inl} + Z_{out}) \quad (2)$$

$$Z_{inl/out} = \left(\frac{A_s}{0.6 \cdot A_{eq,inl/out}} - 1\right)^2 \quad (3)$$

$$A_{eq,inl/out} = A_{top/bot} + \frac{1}{4} A_h \quad (4)$$

Starting from these expressions, two calibration parameters were introduced in the formulation: the first parameter "x" 5 is used to calibrate the area of the openings in order to consider the effect of the discontinuity along the fenestration width of the ventilation openings, and the second parameter "k" 6 to tune the area of the holes of the venetian blinds.

$$A^*_{top/bot} = x \cdot A_{top/bot} \quad (5)$$

$$A^*_{eq,inl/out} = k \cdot \left(A^*_{top/bot} + \frac{1}{4} A_h\right) \quad (6)$$

Additionally, the pressure drop factor K was included in the total pressure loss equation 2, which becomes equation 7.

$$\Delta P_Z = \rho v^2 (Z_{inl/out} + K) \quad (7)$$

The parameters were varied parametrically one at a time: x between 0.1 and 10 and k between 0.1 and 1. The calibration procedure was divided into 2 steps: first, the opening parameter x was calibrated considering only the blind-up configuration, then the shading parameter k was calibrated keeping the x parameter fixed. In this way, the equation 4 becomes 8, forcing identical parameter values for all configurations.

$$A^*_{eq,inl/out} = k \cdot \left(x \cdot A^*_{top/bot} + \frac{1}{4} A_h\right) \quad (8)$$

The optimal values were chosen by minimizing two statistical indicators: the Root Mean Squared Error (RMSE) (9) and the Mean Absolute Percentage Error (MAPE) (10), computed for the inlet mass flow rate and the total heat flux for all the cases considered.

$$RMSE = \frac{1}{N}\sqrt{\sum_{i=1}^{N} (x_{T,i} - x_{C,i})^2} \quad (9)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N} \left|\frac{x_{T,i} - x_{C,i}}{x_{C,i}}\right| \cdot 100\% \quad (10)$$

In this way, the calibration was carried out both at component level (inlet flow rate) and at building level (contribute of the component on the thermal balance of the zone).

3. Results and Discussion

3.1 System Scale Results From COMSOL

The FEM-based simulation performed with COMSOL Multiphysics allowed the temperature, pressure, and velocity field over the fenestration system to be computed and the airflow rate and the total heat flux to be quantified in detail.

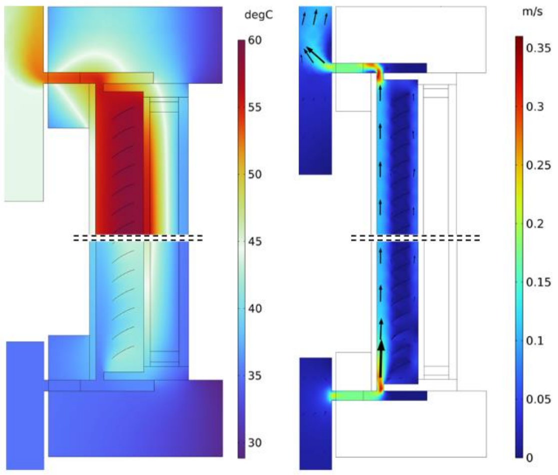

Fig. 3 – Temperature (left) and air velocity (right) distribution over the CFS, $T_{air,ext}$=35°C, $T_{air,int}$ = 28°C, I_{sol} = 500 W/m², blind tilt 30°

To showcase a possible temperature and air velocity distribution over the CFS with a blind tilt angle of 30° and warm summer conditions ($T_{air,ext}$ = 35 °C, $T_{air,int}$ = 28 °C, I_{sol} = 500 W/m²) an illustration of the spatial distribution of the two variables is shown in Fig. 3. It is possible to notice how buoyancy forces the warmer air to rise, resulting in a vertical temperature gradient and leading to high temperatures in the upper part of the CFS, where 60 °C are reached.

3.2 Building Scale Results From TRNSYS and Calibration Parameters

The FEM model outcomes were used to tune the two calibration parameters 5 and 6 of the Python-based Type 169. As mentioned before, only the blind-up dataset was used for the calibration of the x-parameter and focusing on the statistical indicators of the total heat flux, x=0.5 was found to be the optimal solution. Regarding the configuration with the shading system deployed, the x parameter was kept fixed to 0.5 and the parameter k was varied parametrically in order to identify the optimal value which minimizes the statistical indicators for the three blind tilt angles configuration. Fig. 5 shows the outcomes of the calibration procedure with blinds at 30° angle; models with k = 0.3, 0.7 and 1 were compared to the uncalibrated one (x=1, k =1). For each model, the COMSOL (x-axis) versus TRNSYS (y-axis) results are reported for inlet mass flow rate (a) and total heat flux (b). The scatter plots were clustered by the value of the incident solar irradiance, since it affects both the parameters analyzed. It should be noted that parameter k has a greater impact on the mass flow rate than on the total heat flux, because it directly determines the mass flow rate, which in turn influences the total heat flux. Since the flow rate and the total heat flux have different behaviors to the variation of parameter k, the value that minimizes the statistical indicators of the total heat flux was chosen as the optimal one. This assumption is related to the building scale model approach: the total heat flux of the CFS accounts directly for the contribution of the component on the thermal balance of the zone, therefore a greater weight to this parameter is given in the choice of the optimal value.

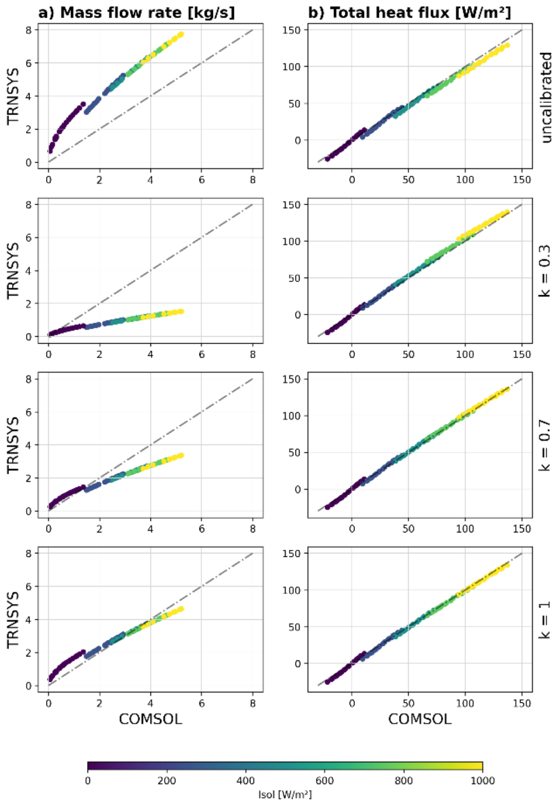

Fig. 4 – Inlet mass flow rate (a) and total heat flux (b) calibration outcomes for blind tilt 30°

The statistical indicator for total heat flux suggests that k=0.7 is the optimal solution, with a reduction of the statical errors of 67 % compared to the uncalibrated model (x=1, k=1). The same calibration procedure was repeated for the other 2 configurations. To avoid redundancy and for sake of brevity, Table 4 summarizes the results of the calibrated model compared to the uncalibrated one in terms of RMSE and MAPE indicators of inlet mass flow rate and total heat flux. A unique value of k parameter was chosen as optimal for all the configurations of the shading system, in order to avoid the need for changing the calibration values x and k for each blind tilt angle.

This, however, leads to a reduction of the model performance, especially with fully closed blinds. Nonetheless, by calibrating x and k parameters for the two extreme conditions (horizontal and fully closed) and one intermediate condition (30°), it can be assumed that the use of these values could be extended for the remaining configurations.

Table 4 – Comparison of RMSE (top) and MAPE (bottom)

Blind mode	Ventilation Type	Mass flow rate	Total heat flux
Blind up	final model	0.19 kg/s 13.2 %	3.12 W/m² 5.6 %
	uncalibrated model	1.59 kg/s 100.8 %	3.74 W/m² 6.7 %
Blind 0°	final model	0.39 kg/s 34.8 %	1.49 W/m² 2.4 %
	uncalibrated model	2.41 kg/s 186.9 %	3.81 W/m² 6.4 %
Blind 30°	final model	0.97 kg/s 37.9 %	1.58 W/m² 1.3 %
	uncalibrated model	2.13 kg/s 125.5 %	4.74 W/m² 5.8 %
Blind 75°	final model	0.98 kg/s 30.9 %	3.42 W/m² 11.0 %
	uncalibrated model	1.67 kg/s 82.7 %	1.88 W/m² 2.0 %

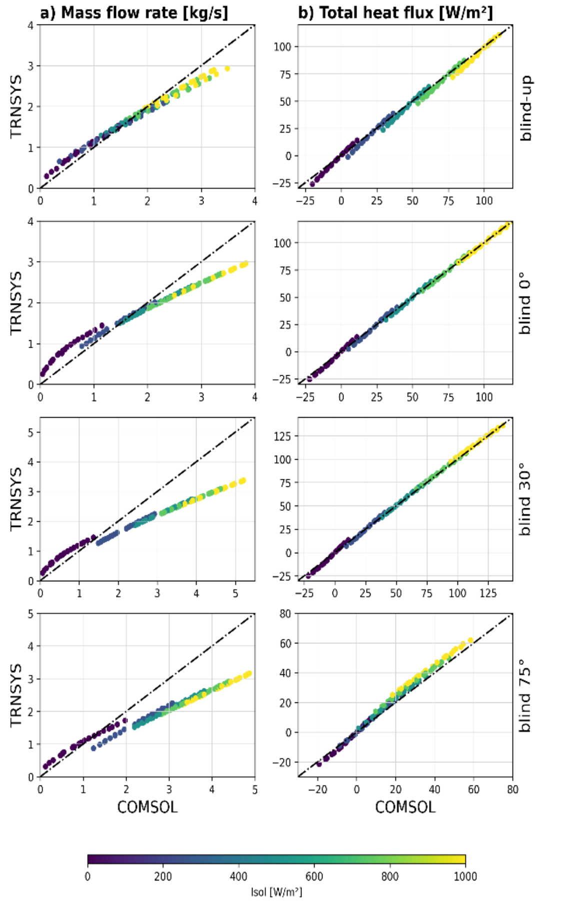

Fig. 5 – Inlet mass flow rate (a) and total heat flux (b) comparison for all blind configurations with the calibrated model

The calibration procedure resulted in a significant reduction of the RMSE in a range of 60 % (blind tilt 0°) to 66 % (blind tilt 30°) and in minimizing the MAPE (especially for blind tilt 0° and 30°). Finally, the comparisons with FEM results for the inlet mass flow rate and total heat flux are shown in Fig. 5 for all configurations. The TRNSYS model overestimates the inlet mass flow rate in the presence of low radiation (< 500 W/m²) and underestimates it in presence of high radiation.

4. Conclusions

To promote the implementation of CFS, it is crucial to enable a relatively simple yet reliable way of assessing their impact at building scale. In this paper, a novel workflow was implemented in one of the most widespread BES tools to assess the performance of a CFS in terms of heat fluxes and airflow rate. The results obtained through FEM simulations were used to calibrate the BES workflow and to assess the error of the calibrated BES tool. Results show a difference of 5 % of the total heat flux through the CFS after the fine-tuning of the ad-hoc Type parameter. The calibration was carried out focusing on the CFS contribution to the thermal balance zone to improve the BES tool's performance in predicting the thermal behavior of such complex components. Moreover, the ad-hoc type can be generalizable for modeling naturally ventilated windows with geometric features similar to the presented CFS (narrow cavity with small vents), since the calibration procedure was carried out by only varying the opening areas.

With this picture, it is possible to state that such workflows allow a consideration of the thermal behavior of CFS at building scale with an acceptable degree of uncertainty. This results in the great advantage of providing the possibility of assessing the impact of a CFS when there is still room for improvement and change in the design.

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Nomenclature

Symbols

q	Specific heat flux (W/m²)
h_c	Convective heat transfer coefficient (W/(m²K))
T_{air}	Air temperature (°C)
T_{sf}	Surface temperature (°C)
σ	Stefan-Boltzmann constant (5.669×10^{-8} W/m²/K⁴)
ε	Thermal emissivity (-)
ε_f	Thermal emissivity front (-)
ε_b	Thermal emissivity back (-)
ρ	Mass density (kg/m³)
u	Air velocity (m/s)
σ_s	Solidity (ratio of blocked area to total area of the screen)
K	Resistance coefficient (-)
λ	Thermal conductivity (W/m/K)
c_p	Specific heat capacity at constant pressure (J/kg/K)

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