CFD and ray tracing to evaluate the thermal performance of Complex Fenestration Systems

Abstract

Complex Fenestration Systems (CFS) can have optical and thermal behaviours dependent from the solar rays' properties and from the air cavity type. The current most detailed calculation methods rely upon the ISO 15099 standard, which let some gaps on how to deal with such CFS. In particular, the optical and convective models might not be adequate for complex blinds and for wide air cavities. In this paper, a CFD+RayTracing method has been setup and applied to both Standard and Complex Fenestration Systems with integrated blinds aiming at validating the approach and quantifying possible discrepancies against the ISO 15099 standard.

Introduction

A relevant part of the building energy demand is due to heating, cooling and artificial lighting. A detailed design of the transparent components and shading devices is crucial to assure indoor comfort while reducing the energy demand. Several studies show the potential of fenestration systems in the reduction of the building overall energy consumption (Lollini et al., 2010; Tzempelikos and Athienitis, 2007) and the enhancement of daylight utilization (Eltaweel and Su, 2017; Koo et al., 2010). To do so, many developments in the shading devices and glazing technologies are ongoing under the umbrella of "adaptive systems" (Loonen et al., 2015, 2013). The term "Complex Fenestration System" (CFS) is used to name all those light transmitting window technologies that include shading devices whose optical and thermal properties present a complex dependence on the angle of incidence and wavelength (Kuhn et al., 2011). These systems include venetian blinds with complex geometries, daylight redirecting systems with specular behaviour and prismatic layers. The angular dependence makes these systems potentially able to provide an improved explicit or implicit management of solar radiation. Moreover, the different possible ways of interaction between the transparent component and the outdoor or indoor air, add a further complexity in the definition of the thermal behaviour of CFS. As consequence, considering the widespread of the use of building simulation software from the pre-design to the eventual post-occupancy optimization, adequate thermal and optical models of the transparent components are essential. The most updated technical standard describing the detailed calculations to model the thermal performance of glazing and shading system is the ISO 15099 (ISO, 2003). However, the applicability of the proposed modelling approach is still to be proven for complex shadings and naturally ventilated cavities. In fact, ISO 15099 refers to standard geometries for blinds, like screens parallel to the window pane or venetian blinds with flat geometries and ideal diffusely redirecting surfaces. Furthermore, the conductive and convective heat transfer within the cavities is computed with a pressure drop model applied to a layer-by-layer approach. This model is based on the opening characteristics of the shading layer that is assumed to be parallel to a window pane. This hypothesis is not true in case of venetian blinds (Hart et al., 2017). Thus, there are some uncertainties in the application of the standard to CFS, in terms of complex blinds' geometries, specular reflecting surfaces and naturally ventilated cavities.

CFD methods are also often used for the analysis of heat transfer through CFS. However, a detailed modelling of solar radiation is difficult to be coupled with CFD simulations, due to its high computational effort. Fuliotto et al. (2010) proposed a decoupled approach, using a radiosity-method based software to simulate the effect of solar radiation. Nevertheless, as far as the optical behaviour is concerned, a very high level of accuracy (McNeil et al., 2013) can be reached by the use of the Bidirectional Scattering Distribution Function (BSDF), which describes the way the light passes through a surface (e.g. a glazing system, one single glass or a shading device). The Three-Phase Method (McNeil, 2014) can describe the way the light is transmitted from the exterior sky vault to the interior environment. Hence, the light path is divided in three parts: the first one from the sky to the exterior of the fenestration (daylight matrix), the second through the fenestration (BSDF) and the third from the interior of the fenestration to the room (view matrix). These coefficient matrices can be multiplied by the sky luminance values and used to perform dynamic daylight simulations for CFS. For a more accurate calculation of the direct component of radiation, the Five-Phase Method (McNeil, 2013), an extension of the Three-Phase one, can be used. These optical models are currently available in the software *Radiance*.

The implementation of the ISO 15099 thermal model and the possibility to characterise the optical properties of the CFS with the BSDF allow the steady-state and transient modelling of CFS also in commercial building simulation software, such as *TRNSYS18* (Klein et al., 2017).

Nevertheless, the uncertainties related to the ISO 15099 thermal modelling applied for CFS have not been quantified yet as well as the benefits of a detailed BSDF based optical model. Moreover, using such model returns a set of outputs related to the centre-of-glass, which can be not representative of critical temperature conditions in the glazing system.

Hence, having a detailed method to manage thermal and optical behaviour of CFS is of particular interest. Uncertainties of ISO 15099 in modelling CFS could be quantified. Moreover, designers and manufacturers would be supported by a detailed toolchain in the identification of critical nodes in the CFS design. In this context, this study presents a modelling approach capable of treating the solar radiation with a detailed optical model based on ray tracing (in *Radiance*) and including the resulting absorbed solar radiation in a comprehensive CFD based thermal modelling (in *COMSOL Multiphysics*). The aim of the work is twofold: assess the validity of the CFD+RayTracing modelling approach on the one side, and quantifying ISO 15099 uncertainties in modelling CFS on the other.

Methodology

First of all, the CFD and the ray-tracing models have been set up and their interaction established. In this modelling approach, solar radiation is treated with a detailed optical model based on ray tracing. The resulting absorbed solar radiation is included in a comprehensive thermal modelling done by coupling heat transfer and fluid flow. Ray tracing analysis performed with *Radiance* enables the calculation of transmitted, reflected and absorbed fraction of solar irradiation for different blind tilt angles and sun positions. The resulting absorbed component of solar irradiation is used as input for the CFD simulations performed with the Finite Element (FE) software *COMSOL Multiphysics*, capable of modelling heat transfer coupled with fluid flow. A comparison between the FE method and the Finite Volume (FV), as implemented in *ANSYS Fluent*, has also been done. This modelling approach has been applied to both standard and complex fenestration systems and compared to the ISO 15099 methods as implemented in *Window7.*

Standard and Complex Fenestration System

In this work two different typologies of fenestration systems were analysed, a Standard Fenestration System (SFS), and a Complex Fenestration System (CFS).

The first modelled configuration can be classified as a standard fenestration system, due to the diffuse reflecting surface of the blinds and its shape. As shown in Figure 1, the system is a double-glazed sealed cavity with integrated diffusely reflecting blinds, which correspond to a type of shading device described also in Annex C of ISO 15099 (ISO, 2003). The blinds have a thickness of 0.6 mm and a width of 16 mm. The pitch between the slats is of 12 mm. Their inclination is fixed at 45°. The cavity, filled with air, has a depth of 75 mm, in compliance with the validity limits of *Window 7.* The glazings are float glasses, while the blinds are made of aluminium. The fenestration geometry and its materials' properties are shown respectively in Table 1 andTable 2.

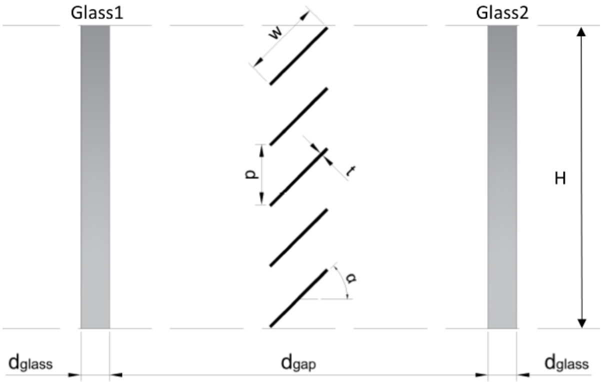

Figure 1: Standard Fenestration System

Table 1: SFS geometry

Symbol	Parameter	Value	Unit
d_{gap}	Cavity width	75	mm
$d_{glass1,2}$	Glass 1,2 width	5.7	mm
w	Blind width	16	mm
t	Blind thickness	0.6	mm
p	Pitch	12	mm
α	Blind tilting	45	°
H	Cavity height	1	m

Table 2: SFS materials properties

Symbol	Unit	Glass 1,2	Air	Blind
λ	W/m/K	1.0	0.024	160
c_p	J/kg/K	820	1006	900
ρ	kg/m³	2500	Ideal	2700
ε_f	-	0.84	-	0.9
ε_b	-	0.84	-	0.9
μ	kg/m/s	-	1.7E-05	-
c_p/c_v	-	-	1.4	-

The complex fenestration system analysed in this work is a triple-glazed window, composed by two sealed cavities and curved commercial blinds with highly reflective surfaces integrated into the exterior cavity (Figure 2). Due to the highly reflective surface given by the coating and the curved geometry, the way the radiation interacts with the CFS depends on the angle of the incident ray. The slat thickness is 0.2 mm and the width 15.9 mm. The pitch between them amounts to 12 mm. The analysis of this configuration is done with a fixed slat inclination of 75° that corresponds to the closed configuration. Glasses 1 and 2 are float glasses, while glass 3 is laminated; their sizes and thermal properties are listed in Table 3 and Table 4. On faces 3 and 5 a low-emissivity coating is placed. The cavities are filled with a gas mixture containing 90 % argon and 10 % air. In the CFD simulation, the physical properties are calculated as a function of temperature (and of absolute pressure for the density).

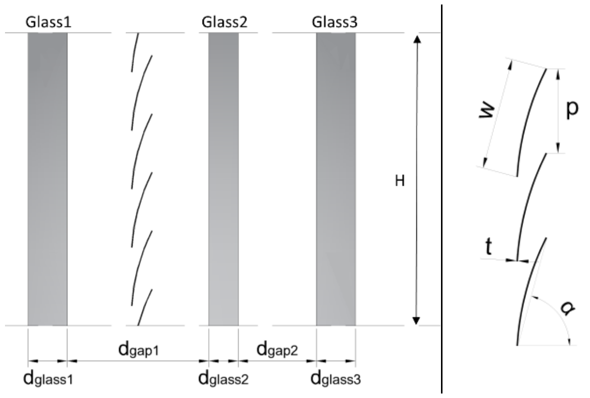

Figure 2: Complex Fenestration System

Table 3: CFS geometry

Symbol	Parameter	Value	Unit
d_{glass1}	Glass 1 width	8	mm
d_{gap1}	Cavity 1 width	29	mm
d_{glass2}	Glass 2 width	6	mm
d_{gap2}	Cavity 2 width	16	mm
d_{glass3}	Glass 3 width	8.76	mm
w	Blind width	16	mm
t	Blind thickness	0.2	mm
p	Pitch	12	mm
α	Blind tilting	75	°
H	Cavity height	0.9	m

Table 4: SFS materials properties. Cavities gas is a mixture of Argon and Air. CFS Glass1 properties are the same as for the SFS

Symbol	Unit	Cavity	Blind	Glass2	Glass3
λ	W/m/K	0.024	100	1.0	0.757
c_p	J/kg/K	1006	900	820	820
ρ	kg/m³	Ideal	2700	2500	2500
ε_f	-	-	0.150	0.037	0.037
ε_b	-	-	0.450	0.84	0.84
μ	kg/m/s	f(T)	-	-	-
c_p/c_v	-	1.58	-	-	-

Solar radiation modelling

Two methods have been used to model the way the solar radiation interacts with the fenestration. The first is the use of the software *Window7* implementing the ISO 15099 optical model and the second the use of *Radiance* for the calculation of the BSDF.

Window7, developed by the Lawrence Berkeley National Laboratory, can be used to calculate the total window thermal performance indexes, like thermal transmittance (U-value), g-value, solar and visible transmittance, etc. Calculation algorithms are based on the standard ISO 15099. For a glazing system with a shading device, the optical properties are calculated considering a normal incidence for the incoming radiation and hemispherically integrated values on the outgoing side. The calculations are based on a layer-by-layer approach, thus the layers composing the glazing unit need to be defined in all their properties and geometries. For the glasses, the required properties are the thermal conductivity and the following spectral averaged values (averaged over different wavelengths): solar transmittance, solar reflectance on the front and backside of the glass, visible transmittance, visible reflectance on the front and backside, infrared transmittance, emissivity on the front and backside. The shading system, in case of venetian blinds, is defined by slat width, spacing between the slats (pitch), tilt angle, thickness and rise. Shading material properties have to be inserted in terms of the spectral averaged values for the transmittance and reflectance, respectively, on the front and backside, averaged over the entire solar spectrum and just over the visible spectrum. In addition to that, the infrared transmittance and the front and backside emissivity are required. The *Window7* calculation procedure can be refined importing a pre-calculated BSDF for the shading system. The BSDF data of the shading system can be either measured with a goniophotometer or calculated with *Radiance*.

Complex shading systems with specular behaviour can be modelled starting from the measured angular reflectance distribution (BRDF) of the material. This material is applied to a 3D geometry representing the shading system. The software *Radiance*, through the tool *genBSDF* (McNeil, 2015) and using ray tracing, generates the BSDF file of the entire shading system. This file, containing the optical behaviour of the shading system, is assigned to the *Window7* software that combines the BSDF of the shading with the properties of the glass layers, in order to get the BSDF for the entire fenestration system. This permits to compute for each direction of incident radiation the direction and share of transmitted and reflected one and the rate of absorbed radiation.

CFD modelling

The CFD simulation work has been done with the FE software *COMSOL Multiphysics* and in some parts also with the FV software *ANSYS Fluent*. The two software have been also compared in order to verify the agreement of the results, especially in relation to the turbulence models. The methodology here described refers to *COMSOL Multiphysics*.

Assumptions

For the calculation of the coupled fluid flow and heat transfer, some simplifications were done. First of all, a vertical section of the fenestration has been considered as 2D domain, assuming a negligible variables variation along the fenestration width. In fact, Pasut and De Carli (2012) investigated the convenience of doing a 3D model. They concluded that there is not an appreciable difference in the results, considering the required additional effort.

Regarding the fluid flow equation, the Boussinesq approximation was used (Versteeg and Malalasekera, 2005). Solar radiation is modelled separately using *Radiance* as described in the previous paragraph. In the CFD tool, the resulting absorbed solar radiation at each layer is then assigned as heat source to each solid as shown in Figure 3.

Long-wave radiation is then exchanged by the solid parts of the fenestration system, due to their relatively low temperatures. Since the long wave radiation exchange has no angular dependence, it is reasonable to treat it with a radiosity approach based on view factors. Thus, in the CFD simulation the radiation exchange is calculated with the so-called surface-to-surface (radiosity) method.

In *COMSOL Multiphysics*, the Conjugate Heat Transfer and the Turbulent Flow interface were used to simulate the coupling between heat transfer and fluid flow. It allows to combine the heat transfer in solids and fluids with the turbulent flow. The coupling also permits the use of the surface-to-surface model for the long-wave radiation exchange.

The fenestration frame has not been modelled, in order to focus only on the centre-of-glass modelling approach.

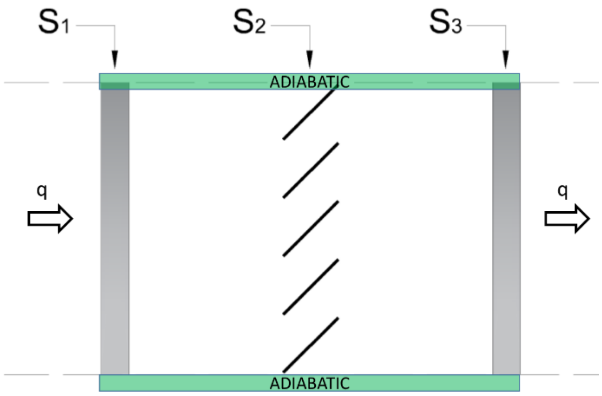

Figure 3: Sketch of the boundary conditions

Boundary conditions

In the CFD calculation, boundary conditions have to be assigned in order to solve the air pressure, velocity, temperature and radiosity over the domain.

For the stationary simulations, standard boundary conditions, according to the National Fenestration Rating Council (NFRC) have been considered (Table 5).

Table 5: Standard NFRC boundary conditions

Variable	Winter	Summer	Unit
T_{ext}	-18	32	°C
$h_{sf,ext}$	25	25	W/(m²K)
T_{int}	21	24	°C
$h_{sf,int}$	7.7	7.7	W/(m²K)
I_{sol}	0	783	W/m²

Third type boundary conditions were assigned to the window faces on the external and internal side, as reported in Equation 1

$$q = h_{sf}(T_{air} - T) \quad (1)$$

where h_{sf} is the global surface heat transfer coefficient, T_{air} is the undisturbed air temperature, while q and T are the heat transfer dependant variables.

In case of winter condition, no optical calculation was done, while for the summer condition, including also solar radiation, the optical behaviour of the sun rays hitting the fenestration system was modelled with *Radiance* and *Window7*. For the standard boundary conditions, the incident solar radiation was assumed to be normal to the fenestration system. The resulting solar radiation absorbed by each solid element was assigned in *COMSOL Multiphysics* as heat rate (Equation 2).

$$S_i = \alpha_i \cdot I_{sol} \quad (2)$$

S_i is the density of heat flow rate of solar radiation absorbed by the component *i*. α_i is the absorption coefficient for component *i*, calculated with the detailed optical model based on BSDF. I_{sol} is the incident solar irradiance.

The top and bottom closures of the cavity were considered as adiabatic.

Turbulence models

In case of fully turbulent flows (high Reynolds numbers), it is possible to skip the integration of the conservation equations in the viscous and buffer region, using analytical wall functions that compute a non-zero fluid velocity at the wall. This so called "wall function" significantly reduces the computational efforts. In case of not fully turbulent flows (low Reynolds numbers), the use of wall function is discouraged (Frei, 2017). Hence, two turbulence models (the "k-ε" and the "Low Reynolds-number k-ε") have been compared in order to choose the most adequate. As further term of comparison, the same fenestration system has also been implemented in ANSYS Fluent, using the "RNG k-ε" model.

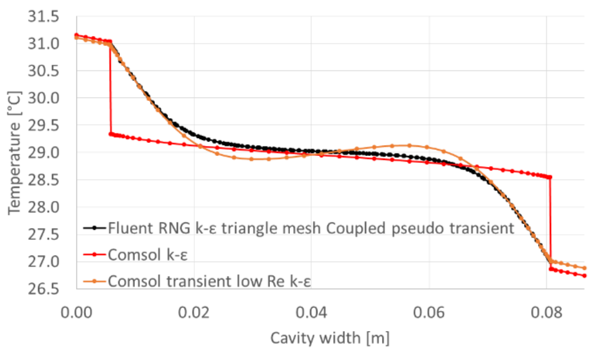

Figure 4: Temperatures along a horizontal cut-line at H/2 for summer conditions without solar radiation. Comparison among the different turbulence models

The results have been plotted in terms of temperature profiles on a horizontal cutline at H/2 (Figure 4). The "k-ε" model shows a steep step of temperatures at the fluid-solid interface, which is not present in both the *COMSOL* "Low Re k-ε" and the *Fluent* temperatures trends. Moreover, these two latter shows a very good correspondence for the majority of points. A small divergence can be noticed at a distance of less than 2 cm from the glasses (with maximum below 1 K in winter without radiation). This justifies the use of the "Low Reynolds-number k-ε" turbulence model in *COMSOL Multiphysics* simulation.

When modelling turbulence using the "Low Re k-ε" model, it has been difficult to get the stationary study to converge and hence the problem has been solved as time dependent. However, the solution of the "k-ε" model has always been used to initialize the transient study, facilitating convergence, resulting in shorter computational times.

Meshing

Different mesh typologies and densities were analysed as reported in Figure 5. The parameter used to evaluate the mesh quality was the overall heat transfer coefficient (U-value), determined in standard winter conditions.

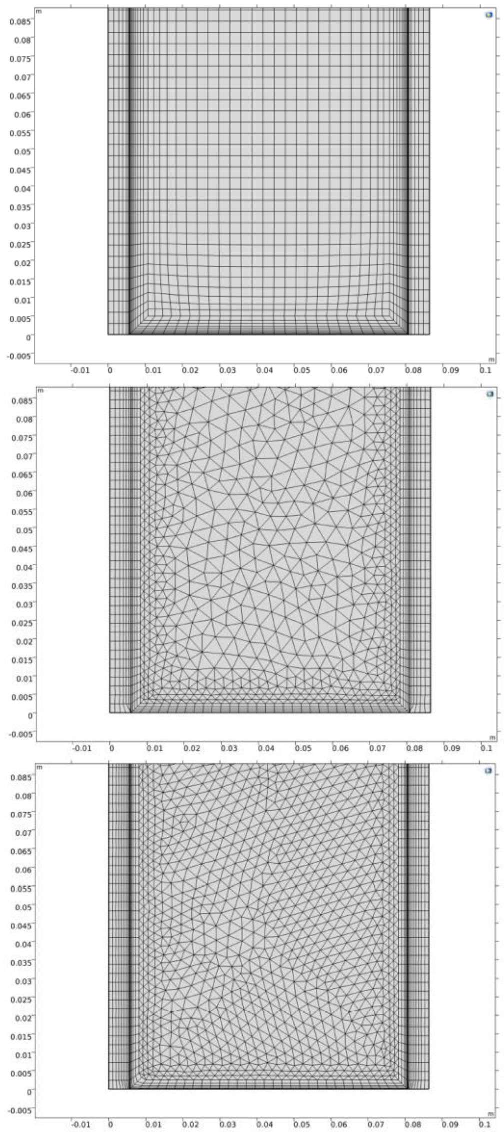

Figure 5: Mesh typologies for SFS without blinds. Normal structured (top); Coarser unstructured (centre); Normal unstructured (bottom)

It can be noticed (Table 6) that there is not a significant difference in the U-value, considering the four finest meshes. However, particular attention has been given to the refinement near the solid boundaries, because the "Low Re k-ε" turbulence model solves the fluid flow equations also in the viscous and buffer layers near the walls, thus a relatively fine mesh is needed there.

The adopted mesh in case of the presence of blinds is the unstructured normal as for the case without blinds and it can be seen in Figure 6 for the standard fenestration with blind system. An inflation layer around each slat has been built and the mesh was refined in the area surrounding the blinds, in order to be able to solve the fluid flow around the lamellas.

Table 6: U-value for SFS without blinds with different mesh elements number

Mesh	**Quality**	**Number of elements**	**U-value [W/m²/K]**
Unstructured	Extra coarse	4492	2.4443
Structured	Coarser	10640	2.4548
Unstructured	Coarser	13946	2.4563
Structured	Normal	19424	2.4567
Unstructured	Normal	20862	2.4567

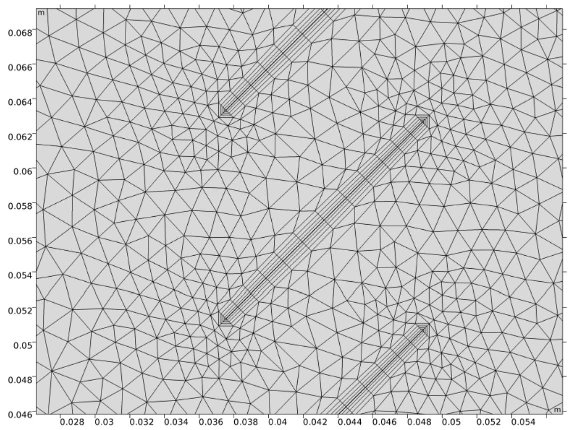

Figure 6: Mesh for SFS with blinds - zoom around the blinds

The problem was solved as a time-dependent one, with stationary boundary conditions. Each time-step was considered to be converged if the normalized residuals of the continuity, momentum and energy equations were reduced to less than 10^{-3} and the simulation was run until the temperatures stabilized around a certain value. Typically, 2400 s were needed until a stable solution was found. The discretization order was chosen comparing the results and the computational effort for different schemes. Finally, for the velocity and temperature a second-order scheme, while for the pressure and radiosity a first-order one was used.

Summary of simulations and KPIs

The comparison between the CFD+RayTracing and the ISO 15099 methods have been implemented for the fenestration systems and boundary conditions as summarized in Table 7.

Table 7: Simulated systems and boundary conditions

Fenestration	**Blind**	**NFRC BC**	**Short name**
SFS	No	Summer	SFS-w/o-summer
SFS	No	Winter	SFS-w/o-winter
SFS	Yes	Summer	SFS-w/-summer
SFS	Yes	Winter	SFS-w/-winter
CFS	Yes	Summer	CFS-w/-summer
CFS	Yes	Winter	CFS-w/-winter

For each fenestration configuration, the following key performance indexes (KPIs) have been calculated and used to compare results obtained with the different simulation tools. Glazing, blind and air temperatures have been considered as maximum, minimum and average, this

latter for different integration areas. Thermal transmittance (U-value) and solar heat gain coefficient (g-value) have been derived as indicated in the ISO 15099 from the calculated heat flux rates.
The KPIs calculation in the CFD tool has been done considering different integration lengths. In particular, starting from the horizontal cut line at H/2, three different lengths have been considered: dH/5, dH/2 and full height dH (as sketched in Figure 7).

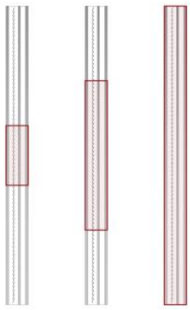

Figure 7: heights for the calculation of the averages and integrals. dH/5 (left); dH/2 (mid); dH (right)

The dH/2 scenario has not been used as it does not give any significant advantage. On the contrary, dH/5 has been used as reference for the calculation of the centre-of-glass averages for the temperatures. Nevertheless, for the U- and g-values the full height H has been used for the heat flux integration.

Results and discussion

SFS, winter, w/o blinds

The differences between the temperatures resulting from *CFD-based* model and the *Window7* (see Table 8) are quite low, especially if the average temperatures of the entire glasses are considered. To be consistent with the window centre-of-glass results, also for the CFD simulation the temperature resulting at the centre of the glass should be used in the comparison. In this case, the difference is a bit higher, but reaches a maximum of 0.72 °C. The U-values are consistent with the temperatures. The overall U-value computed with COMSOL is 4.67 % lower than that resulting from the *Window7*. Hence, for the SFS without blinds a good correspondence between results from the CFD simulation and the ISO 15099 model in *Window7* has been found.

Table 8: Results comparison COMSOL and Window7 for the SFS without blinds in winter

		Window7	**COMSOL dH/5**	**COMSOL dH**
T1	°C	-13.70	-14.00	-13.89
T2	°C	-13.10	-13.44	-13.31
$T_{dgap/2}$	°C	-	-3.29	-3.14
T_3	°C	6.40	7.15	6.95
T_4	°C	7.00	7.72	7.54
U	*W/m²/K*	2.765	2.581	2.636
ΔU/U	%	-	-6.66	-4.67

SFS, summer, w/o blinds

As reported in Table 9, the surface temperatures resulting from *CFD-based* model do not present important variations compared to the *Window7* results. The highest one occurs on face 2 and amounts to 0.06 °C. Also for the g-value, there is no significant difference between the results of the two methods. For the computation of the g-value, the solar transmittance τ_e resulting from *Window7* was added to the secondary heat flux q_i resulting from the CFD simulation.

Table 9: Results comparison COMSOL and Window7 for the SFS without blinds in summer

		Window7	**COMSOL dH/5**	**COMSOL dH**
T_1	°C	37.00	37.00	37.00
T_2	°C	37.40	37.34	37.34
$T_{dgap/2}$	°C	-	36.86	36.86
T_3	°C	36.40	36.38	36.37
T_4	°C	36.10	36.10	36.09
g	-	0.697	0.697	0.697
Δg/g	%	-	-0.07	-0.05

The resulting secondary heat flux q_i amounts to 9 %, in case of a double-glazed cavity without shading system and normal incident radiation of 783 W/m². This means that the heating up of the fenestration system due to the solar absorption, causes a heat flux to the indoor environment of 71.3 W/m². In addition to that, a heat flux due to solar transmission of 475.3 W/m² enters the room.

Table 10: Secondary heat flux, solar transmission and g-value for SFS w/o blinds

q_i	τ_e	g
0.090	0.607	0.697

SFS, winter, w/ blinds

For this configuration with integrated standard slats, results are summarised in Table 11. The discrepancies are low between the temperatures obtained with *CFD-based* model and *Window7*. Considering the glass surface temperatures averaged over the total height, the highest difference occurs at face 4 and amounts to 0.32 °C. A very good correspondence has been found also for the U-value of the entire glazing component.

Table 11: Results comparison COMSOL and Window7 for the SFS with blinds in winter

		Window7	**COMSOL dH/5**	**COMSOL dH**
T_1	°C	-14.30	-14.51	-14.32
T_2	°C	-13.80	-14.03	-13.81
T_{blind}	°C	-2.30	-2.33	-2.41
T_3	°C	8.40	8.53	8.15
T_4	°C	9.00	9.03	8.68
U	*W/m²/K*	2.373	2.264	2.363
ΔU/U	%	-	-4.59	-0.41

SFS, summer, w/ blinds

In case of SFS with blinds and summer NFRC conditions, the correspondence of the surface temperatures between

CFD-based model and *Window7* is very good (Table 12). This latter underestimates the blind temperature by 2.88 °C compared to the one at the centre of the cavity height. For the g-value a very good correspondence has been found. This implies also that the secondary heat flux computed with *CFD-based* model corresponds to the one estimated by *Window7*, because in both cases the solar transmission resulting from *Window7* is used.

Table 12: Results comparison COMSOL and Window7 for the SFS with blinds in summer

		Window7	**COMSOL dH/5**	**COMSOL dH**
T_1	°C	43.70	44.08	43.83
T_2	°C	44.90	45.34	45.04
T_{blind}	°C	63.50	66.38	65.12
T_3	°C	33.80	45.40	44.79
T_4	°C	44.00	44.56	43.98
g	-	0.299	0.303	2.363
$\Delta g/g$	%	-	1.44	-0.62

CFS (w/ blinds), winter

As emerged from Table 13, the correspondence of the surface temperatures obtained with *Window7* and *CFD-based* model is very good for the exterior and the room side glass, while for the central glass pane, the difference is higher and amounts to approximately 1.78 °C as maximum.

For the U-value of the CFS, slightly higher divergences than those obtained for the SFS has been found between the two models. Considering the COMSOL results for the entire glazing, which is thought to be more representative of these simulation results, *Window7* overestimates the U-value by 7.98 %. This divergence could be due to the *Window7* model of the convection, which influences the heat transfer and, therefore, the U-value. Hence, in this case, the advantage in using a *CFD-based* approach can be seen.

Table 13: Results comparison COMSOL and Window7 for the CFS (with blinds) in winter

		Window7	**COMSOL dH/5**	**COMSOL dH**
T_1	°C	-17.00	-17.18	-16.98
T_2	°C	-16.80	-17.01	-16.77
T_{blind}	°C	-9.50	-10.82	-10.33
T_3	°C	1.30	-0.43	-0.42
T_4	°C	1.50	-0.28	-0.26
$T_{dgap/2}$	°C	-	8.72	8.61
T_5	°C	17.50	17.66	17.40
T_6	°C	17.80	17.95	17.72
U	$W/m^2/K$	0.638	0.564	0.587
$\Delta U/U$	%	-	-11.52	-7.98

CFS (w/ blinds), summer

Similarly as in winter conditions, for the surface temperatures of the exterior and room side glass pane a good correspondence could be found between *Window7* and the *CFD-based* results (Table 14). Instead, for the central glass, a higher divergence can be seen. On face 3, for example, the temperature difference, considering the centre of glass values, amounts to 3.72 °C. This is also an indicator for the cavity temperature between the blinds and the central glass pane. Nevertheless, for the blind temperature a very good correspondence could be found. Considering the averaged centre-of-glass values, the highest difference amounts to 0.22 °C. Instead, from the CFD analysis the highest blinds' temperature resulted to be up to 70 °C and occurs in the upper part of the cavity. Hence, when the aim is investigating extreme temperatures, the CFD analysis would be more helpful.

Regarding the g-value (Table 14), a relevant relative divergence has been found using the *Window7* averaged spectral data as input. The *CFD-based* g-value is higher by 29.35 %. Instead, if *Window7* is enriched with a detailed optical model (i.e. the BSDF) for the shading system, the correspondence between the results from the CFD coupled with ray tracing and *Window7* is nearly perfect. This result underlines the importance of the BSDF for complex shading systems. However, a higher discrepancy between CFD and *Window7* even with BDSF is expected for wider and higher air cavities configurations. In fact, in these cases, the convection tends to be more difficult to be predicted without CFD.

It is interesting to notice, that the secondary heat flux constitutes 59 % of the overall g-value.

Table 14: Results comparison COMSOL and Window7 for the CFS (with blinds) in summer

		Window7 ([1] +BSDF)	**COMSOL dH/5**	**COMSOL dH**
T_1	°C	42.60	41.53	41.51
T_2	°C	44.00	42.83	42.80
T_{blind}	°C	66.70	66.92	65.57
T_3	°C	52.60	56.32	55.14
T_4	°C	52.40	56.15	54.98
$T_{dgap/2}$	°C	-	43.25	42.97
T_5	°C	30.00	30.83	31.01
T_6	°C	29.50	30.31	30.47
g	-	0.068 (0.088[1])	0.092	0.088
$\Delta g/g$	%	- (29.41[1])	35.43 (4.5[1])	29.25 (0.1[1])

Conclusions

The presented study reports about a CFD+RayTracing modelling approach for CFS, able to characterise the temperature field and the secondary heat fluxes. This approach is based on the detailed modelling of the optical properties through the BSDF and the implementation in a CFD software of the energy absorbed at each layer of the CFS. The comparison for steady-state BC against the ISO 15099 models, implemented in the software *Window7*, show a good agreement for SFS with and without blinds in terms of U- and g-values. In fact, the differences remain well below the 10 %.

For CFS, CFD and ISO 15099 methods lead to 8 % difference in the U-value calculation for the considered case. In case of radiation, the need of using the BSDF as input for the optical model also in *Window7* has been highlighted, in order to avoid relative errors up to 30 % on the g-value. With the most accurate input, then, the g-values discrepancies are below the 5 %. However, the benefit of modelling the fenestration with a CFD tool is expected to be larger in case of wider (or naturally ventilated) cavities, because of the more complex convection.

Given the soundness of the here presented CFD+RayTracing approach, the following next steps have been foreseen. First, a comparison against measured data will be done for a venetian blind system integrated in a triple glazing. In this case, the influence of the frame modelling will be also assessed. As second step, the modelling procedure will be applied in a parametric way to different cavities depths and ventilation modes and compared to the ISO 15099 modelling approach.

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