397: Double-skin façade exhaustive simulation throughout combined thermal and daylight modelling. Application to optimal control

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Abstract

To optimize the comfort (visual and thermal) and energy savings, the topics related to solar protection are getting more and more important. Indeed it is necessary to use the maximum of the sun in winter (avoiding the glare) and to minimize transmitted radiation during the hot season in order to avoid the space overheating. The double-skin facades (DSF) satisfy these two goals. An exhaustive modelling of DSF has been realised. The studied DSF are equipped with Venetian blinds and provided with mechanical ventilation. The impact of this façade on the indoor environment in terms of visual and thermal ambiance is analysed. Our global simulation model is represented by a set of sub models, each characterising thermal behaviour of the DSF, natural and artificial lighting. All these simulation models are coupled with an office zone and then implemented in SIMBAD (HVAC Simulator for Building and Devices). Detailed descriptions of these implemented models as well the validation procedures are presented in the paper.

Keywords: double-skin façade model, solar radiation, double-skin façade simulation, indoor comfort, control.

1. Introduction

Double-skin façades (DSF) are highly technological building components which are deployed to use maximum of sun in winter (avoiding the glare) and to minimize transmitted radiation during the hot season in order to avoid space overheating. Used in new architectural projects, DSF are designed to fulfil several envelope functions, such as thermal and acoustic insulation, optimization of natural lighting and improvement of ventilation system.

In addition to the envelope itself (façade), a DSF have a second glazed layer (with a non-structural role) placed at a certain distance from the inner layer [1]. These two sheets of glass act as an insulation between the outside and inside enabling the air to circulate between the two façade's skins. The distance between glass layers varies from few centimetres to over one meter. The zone positioned between these two layers is named buffer zone or "cavity" and generally is ventilated. It must reduce overheating during hot periods, preheat the ventilation air during cold periods and then must contribute to energy savings.

2. Double-skin façade model

A single storey double-skin façade type was selected for investigation [2]. In this respect, a full sized double-skin façade incorporating a sun-shading blind was studied. The real double-skin façade studied here, presented in Fig. 1, is realized of two aluminium frames. The DSF includes four openings for ventilation (height of 0.04 m).

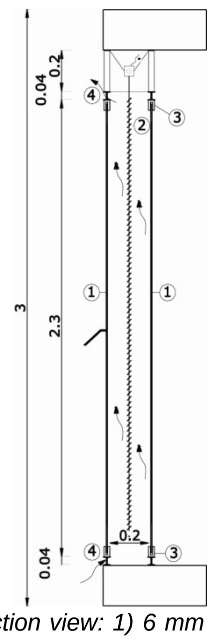

Fig 1. DSF section view: 1) 6 mm glass layer; 2) solar protection (blade width W=0.025 m); 3) aluminium frame; 4) ventilation openings.

The openings cover the whole width of the façade, at the top and bottom of each of the two panels. Thus, various configurations of the ventilation of the double-skin can be tested by simple obstruction of these openings. The sun-shading devices are Venetian type blinds placed in the middle of the DSF cavity. The DSF is mechanically ventilated.

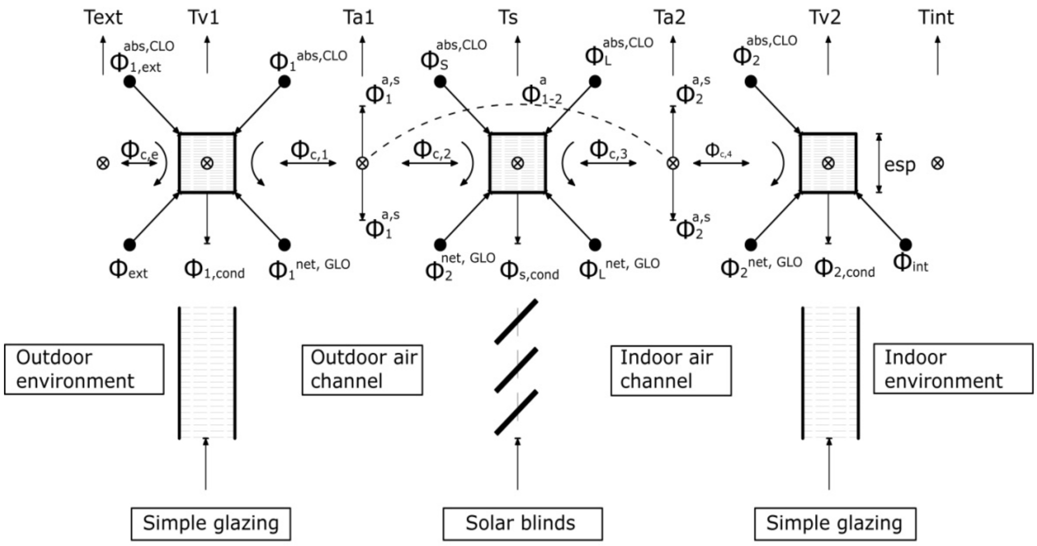

Fig 2. DSF global model

The simulation model is represented by a DSF equipped with Venetian blinds and external mechanical ventilation. The model is a two-dimensional representation, dividing the height of DSF into a number of horizontal bands. Each horizontal band is divided into 5 nodes characterized by their temperature (Fig. 2). The model can be modified easily to take into account an extra layer of glass on the outdoor or indoor pane (for the DSFs with double glass). In this case an extra temperature node is introduced in the model scheme. The energy balance is written in every node of each vertical band. Long and short wave radiation, convection and conduction heat exchanges and heat flow due to the mass transfer in the cavity of the façade are represented (Fig. 2). It should be mentioned that the model was established by confrontation to CFD simulations and PIV measurements, presented in [3], [4]. Elements such as solar protection angle, ventilation flow inside the channel, sun angles, thermal characteristics of skins and outdoor conditions are included in the experimental confrontation process.

In the first step a DSF model was developed in SIMBAD (MATLAB®/Simulink® environment) and coupled with a zone model. The coupling is done according to following three actions. For each time step: (i) the average temperature of the DSF inner glazing is introduced in the zone module that calculates the walls surface temperature; (ii) the solar radiation transmitted through the DSF is introduced as well in the zone model; (iii) the calculated zone temperature is used in the DSF model for calculations of convective heat flow between the façade and the indoor air ([5]).

The DSF model was validated in a full scale completely controlled environment. A DSF system was installed in climatic test-cell with imposed and controlled boundary conditions. The DSF was exposed to the controlled climatic conditions (temperature and solar radiation), provided by a full scale weather generator and a solar simulator.

3. Weather and solar radiation modelling

The DSF receives an external solar radiation which is appeared as a diffuse component coming from the sky and as a direct component coming from the sun. For daylight calculations, it is the illumination which it is necessary to use. This one is distinguished from the radiation by the taking into account the spectral relative sensitivity of the eye.

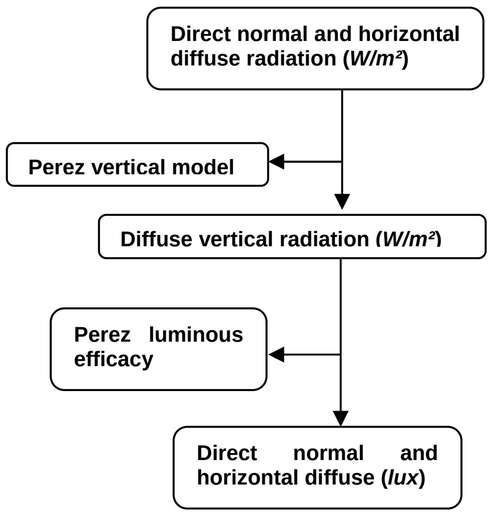

Fig 3. Modelling the solar radiation

The weather files generally do not provide the external illuminations on surfaces. Generally, they provide the diffuse radiation on a horizontal surface as well as the normal direct radiation (i.e. in a plan perpendicular to the rays). The weather model presented here makes possible to pass from the diffuse horizontal and direct normal

radiation to the vertical illuminations. The complete model is depicted in Fig. 3 ([6]).
The implemented weather models allows as well computing the solar angles (zenith, azimuth, sun height, incidence angle) together with solar radiation and luminous flux on the desired vertical surface. These parameters are essential for other models.

4. Light modelling

The light models presented in this paper are realised to take into account particularly the visual comfort. Moreover, these models are taking into account the energy savings due to the coupling between daylight and artificial light. This situation is possible, function of daylight, modulating the power of the artificial light system inside the simulated zone. Since the daylight is depending of the DSF, is very important to take into account the influence of the façade elements. Daylight and artificial light systems allow the correction of the artificial light to complete the daylight and to reach the recommended light level for the occupants.

4.1 Daylight

The daylight model starting point is the geometry of the studied zone. In this studied case the geometry is simple, a parallelepiped with one side occupied entirely by the DSF. To compute the luminance, the wall surfaces are considered as perfectly diffusing the light. For every surface the illumination is calculated on a generated mesh. This resulting illumination is the sum between the direct and diffuse illumination. The direct component of the diffuse illumination takes into account the light fluxes arriving from the DSF on the element dS_P (see Eq. 1).

$$E_{P,dD} = F_{DSF} \cdot \frac{\Phi_{d,DSF}}{S_{DSF}}$$

(1)

Where: F_{DSF} is the form factor between dS_P and the façade, $\Phi_{d,DSF}$ is the diffuse luminous flux transmitted by the DSF and S_{DSF} the DSF area.
A simplified model is used for modelling, the multiple reflection of the diffuse illumination inside the zone (see Fig. 4).
The formula used here (Eq. 2) is called "split-flux" [7].

$$E_{P,dd} = \frac{2 \cdot (0.39 \cdot \rho_{fw} + 0.05 \cdot \rho_{cw}}{(1-\bar{\rho})} \cdot \frac{\Phi_{d,DSF}}{S_{DSF}}$$

(2)

Where: ρ_{fw} is the lower part wall mean reflection factor, ρ_{cw} is upper part wall mean reflection factor and $\bar{\rho}$ is the wall mean reflection factor.
Similarly, direct and multiple reflections component of the direct illumination are treated.

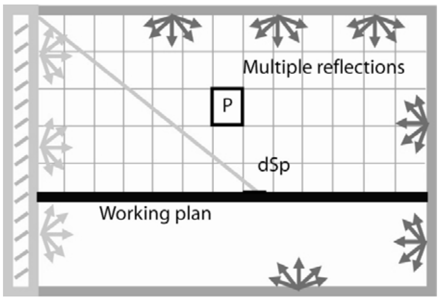

Fig 4. Light modelling ([8])

The global illuminance received by the cells of the mesh on the walls or on the working plan is the sum of all direct and diffuse components (Eq. 3).

$$E_{P,total} = E_{P,dD} + E_{P,dd} + E_{P,DD} + E_{P,Dd}$$

(3)

Where: $E_{P,dD}$ is the direct component and $E_{P,dd}$ the multiple reflection component of the diffuse illumination, respectively $E_{P,DD}$ is the direct component and $E_{P,Dd}$ the multiple reflection component of the direct illumination. The daylight model was tested and validated using data from two European research projects [9] and [10].

4.2 Artificial light

The artificial light is computed to provide a uniform illumination on the working plan. For this model is not necessary to mesh the space. A mean illumination interpretation on the working plan is more adequate. The artificial light model is based on the French standard NF 71-121 [NF C71-121, 1993]. The calculation method gives the average illumination on the working plan and on the walls. Calculation is fast since it is based on results obtained for reference systems. Illuminations are obtained starting from the concept of utilance. The utilance is described as the relationship between total illuminance reaching the useful plan and total illuminance leaving the luminaries. As for daylight calculations, total illumination reaching the working plan is the sum of a direct component and a component of multiple reflections.
The direct component depends on the distance between surface and luminaires and on the space distribution of luminous flux leaving the luminaire. To characterize this distribution, the luminaire class concept is used. This characteristic is generally given by the luminaire manufacturer. Illumination calculations are

carried out once, before starting the simulation. They make it possible to check the number of luminaires, as well as the light flux delivered by each luminaire. As well, this model verify if is sufficient light inside to obtain the desired illumination recommended for the activity of the occupants. Illuminations recommended are given by the CIE [12].

5. Simulation platform

5.1 Auxiliary models

The auxiliary models such zone model, weather data, HVAC unit, etc., are provided by the SIMBAD HVAC library. SIMBAD library is a HVAC toolbox for the MATLAB®/Simulink® environment. The toolbox provides ready to use HVAC models and related utilities to perform transient simulation of HVAC plants. This toolbox offers, in connection with other existing toolboxes (Neural network, fuzzy logic, optimisation…), a very powerful and efficient tool for design and test of controllers. The models are developed either completely in the Simulink® block diagram language, in MATLAB®/code or in compiled C-code. The source codes of modules written in C-Language or MATLAB®/language are provided. The open structure of the models enables the users to modify them and personalise the models. The user can view graphically the functional scheme of the model by "entering into" the inner layers of the models. The number of innermost levels differs from one model to another according to their complexity. The developer of the models defines these layers by using built-in masking functions of the Simulink® environment to create dialogue boxes.

5.2 Coupling of the models to zone model

All the models presented above are coupled to create a fully dedicated platform for the simulation of the DSFs. This platform can simulate the coupled systems all year long in order to optimise the comfort (visual and thermal) and the energy savings.
Fig. 5 shows the simplified coupling scheme between the studied models. A new block is necessary here, to control and optimise the functioning of the rest of the models. This control block implements a set of rules which are supervising the other components. Moreover, this control system interchanges information between all the blocks and reacts quickly in order to adjust the visual and thermal comfort.
The rules imposed here take into account a set of priorities to minimize the conflicts that may appear.
For example, during the occupation of the zone, the control system is focussing only to comfort. During inoccupation period instead, the control is maximising the energy savings. Another goal of the controller is to avoid glare inside, function of the outdoor conditions and the DSF characteristics. The controller manages as well the illumination (daylight and artificial) on the working plan and the indoor air temperature.

6. Results

Fig. 6 shows the weather evolution during a clear sky winter day (January) in the south of France. In Fig. 6 are presented the external direct and diffuse solar radiation arriving on the vertical south oriented DSF.

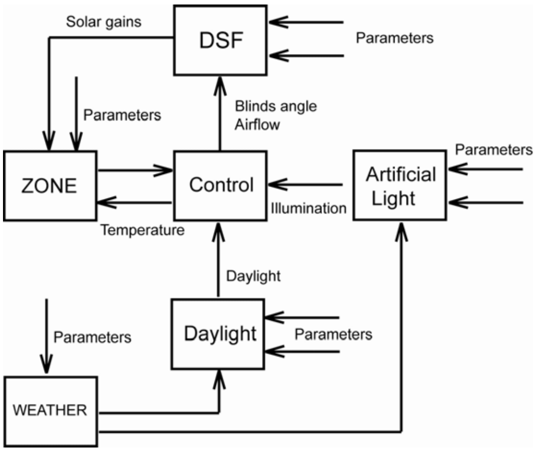

Fig 5. Coupling scheme of the zone model with DSF, daylight and artificial models

Due to outdoor environmental factors the indoor temperature varies consequently. In the first part of the day the indoor air temperature is maintained at a level permitting energy savings (15°C). Before occupation, early in the morning the temperature controller reacts and increases the temperature to a comfortable value.

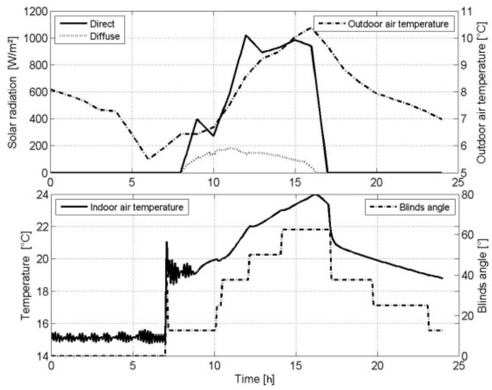

Fig 6. Full system winter case simulation

Together with the temperature, the DSF blinds are oriented function of the indoor characteristics defined in the controller. Due to important solar gains in the first part of the day, the heating system is rapidly turned off. For the rest of the day, the zone is heated only with the gains (external and internal). A maximum level of temperature is reached simultaneous with the outdoor conditions. The blinds are oriented with the respect to daylight, to correct the growth of the temperature over the cooling limit.

Fig. 7 shows the simulation results during a sunny summer day (July). Because the façade is south oriented and because the sun altitude is important, during the summer the direct solar radiation is limited.

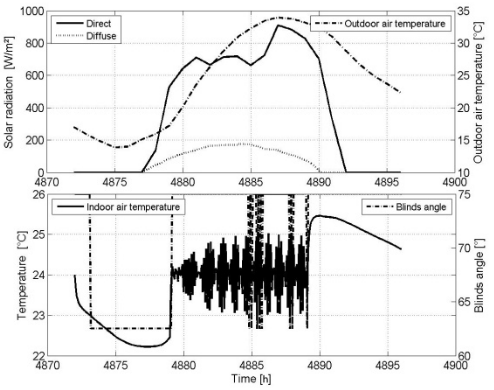

Fig 7. Full system summer case simulation

In Fig. 7 the indoor air temperature is maintained during occupation at comfortable level (24°C) using the cooling systems. The passive elements (blinds, DSF ventilation) of the façade cold not limit the increase of the temperature. At inoccupation, to save energy, the indoor air temperature is maintained at overheating setpoint (28°C). During the day the DSF blinds are closed for the majority of the time.

7. Conclusions and perspectives

Numerical simulations presented in this study showed that double skin facade is a promising system for energy savings. In spite of significant glazed surface a double-skin facade contributes to the energy saving.
The proposed controller enables correctly the energy performance. Moreover the study showed that the benefits can be increased by better integration of the building and DSF ventilation. Future work will consider the DSF as heat recovery system or pre-heater for the ventilation air.
For the perspectives, a more complete analysis is to be considered, focussing not only to the thermal and visual aspects, but also to the energy savings. The energy savings are to be evaluated during all year long. Moreover, various external conditions must be tested to evaluate the system during spring and autumn.
Future work will focus as well on the improving of the control strategies. New capabilities are to be implemented. For example, the performance of actuators is to be studied, as well the discomfort induced by the continuous movements of the blinds (limitation of allowed adjustments per certain period of time).

8. Acknowledgements

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