MODELING OF THE DOUBLE-SKIN FACADES FOR BUILDING ENERGY SIMULATIONS: RADIATIVE AND CONVECTIVE HEAT TRANSFER

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ABSTRACT

A comprehensive modeling of radiative and convective heat transfer of a compact double-skin facade equipped with venetian blind is proposed here. Results from detailed CFD model were used in order to compute convective heat transfer coefficients and the radiation heat transfer, parts of energy balances of the proposed nodal model. The convective heat transfer coefficients found were weak and only little influenced by slat tilt angles and solar radiation. On the opposite the slat tilt angle effect on radiative heat transfer is very important, since it regulates the solar radiation transmitted to the inside.

INTRODUCTION

Nowadays different kinds of double-skin facade are developed and used in new architectural projects. The interest of these facades is, on one hand to increase the human comfort and on the other hand to decrease the energy consumption. In order to optimize the thermal performance of the double-skin façades, their detailed behavior needs to be better understood. In addition their models must be adapted for building energy simulations and need to be established. Concerning the geometry of the facade, we are interested here in a compact one floor double-skin façade equipped with venetian blind.

The double-skin facade behavior depends on many parameters such as orientation, the geometry, the ventilation strategy, solar protections, etc. The location and the orientation of the double-skin facade define the collimated beam radiation (direction of the direct solar radiation and incidence angle). The slat tilt angle and the lateral distance (glazing-blind) influence the air flow inside the facade. Finally, the position of the air inlet and the mass flow rate for the forced ventilation describe the velocity field.

The present work is the second part of a project dedicated to the study of double-skin facade behavior. The first part of this project was a parametric study dedicated to the analysis of the impact of: the solar radiation, the slat tilt angle, the lateral distance (glazing-blind) and the air flow rate on temperature and velocity fields inside the channel of the double-skin facade. As the detailed description of temperature and velocity fields was of interest, the numerical simulations were performed using detailed CFD approach. This part showed that the double-skin facade behavior depends on several linked parameters (Safer et al., 2004a; Safer et al., 2004b; Safer et al., 2005):

- The direct solar radiation is an important parameter since it modifies significantly the velocity and the temperature fields inside the channel. In this case, the buoyancy effects are important and predominant, even when mechanical ventilation is used. This predominance is changed towards the forced convection when the mass flow rate increases.
- The slat tilt angle effect on temperature and velocity fields inside the channel is limited. Nevertheless, it is still a very important parameter for global approach of buildings since it regulates the solar radiation transmitted to the inside.

However, CFD tools are suitable for detailed analysis of the façade but are not well adapted for building energy simulation, mainly because of high computational time and very detailed description of the element needed (Hensen et al. 2002). Therefore the objective of this second part is to design a global double-skin facade model. Most of the existing models are based on nodal approach and use literature formula where the temperature field is neglected and velocity field very simplified (Hensen et al. 2002, Arons, 2000, Sealens et al. 2003). The ambition of this paper is to propose a more accurate nodal model, using radiative and convective heat transfer coefficients based on velocity and temperature fields inside the channel computed using CFD. More precisely, this investigation is focused on the quantification of:

- The radiative components such as the transmitted, absorbed and reflected radiation for the internal and external glazing and for the blind.
- The convective heat transfer coefficients inside the channel of double-skin facade for the air-

blind, the air-external glazing and the air-internal glazing.

After the description of the double skin façade treated, the main hypothesis and results of the detailed model are presented in the following sections. Then the convective and radiative heat fluxes are computed in several configurations depending upon as beam radiation, slat tilt angle and so on. Finally, a brief presentation of the methodology adopted for the establishment of the double-skin global model is discussed.

CASE DESCRIPTION

A lot of bibliographical studies were dedicated to the double-skin facade (Faist, 1998; Arons, 2000; Saelens, 2002; BBRI, 2004). These studies have showed that double-skin classifications are commonly based on geometrical parameters and channel ventilation strategies. Geometrical parameters include height and width of the facade, width of the channel, type and position of the solar protection, etc. Channel ventilation strategies include the type of ventilation (natural, mechanical or hybrid) and the description of the air path (outside-channel-outside, outside-channel-inside, etc).

In the present work, we are interested in a compact one floor double-skin façade geometry: 3 meters high and 1.50 meters long, with the channel width of 20 cm. This facade is equipped with usual venetian blinds (25 mm slats) placed inside the channel. However, because of the continuity of the geometry and the airflow configuration according to the third axis, the airflow is essentially 2D. Therefore the numerical simulations will be conducted in the 2D configuration (figure 1).

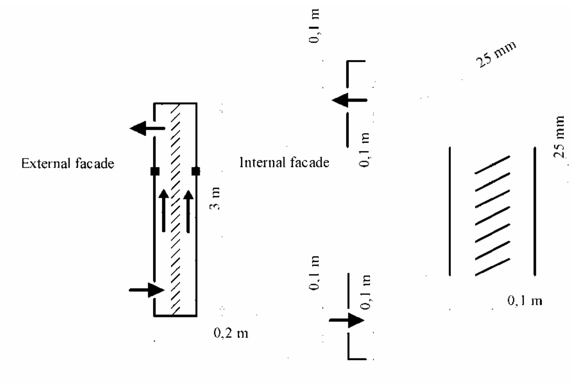

Figure 1 Double-skin façade geometry.

As stated before, the double-skin façade is composed by an external and internal glazing. The external is a simple glazing of 12 mm and the internal one is a double glazing of 6+12+6 mm. The radiative characteristics concerning our compact double-skin façade are the refractive index and the absorption coefficients (the extinction coefficient).

The refractive index of each component is given in the following table.

Table 1
Refractive index

COMPONENT	REFRACTIVE INDEX
Air	1.0
Glazing	1.5

The blind is made of aluminum with an emissivity of 0,15.

For better consideration of solar and infrared radiations, the absorption coefficients are given according to four wavelength bands.

Table 2
Extinction coefficient

BANDS	EXTINCTION COEFFICIENT [M^{-1}]
0 – 0.78 µm	10
0.78 – 2.7 µm	10
2.7 – 4.5 µm	1000
>4.5 µm	5000

The extinction coefficients presented in Table 2 concerns a usual simple glazing (Heping et al.).

For a better understanding of the overheating inside the channel of the double-skin, a south orientated façade is simulated at solar noon in summer conditions. Also, for the same reasons the direct and the diffuse solar radiations are given according to four wavelength bands. The weather data used are from Nice, located in the south of France.

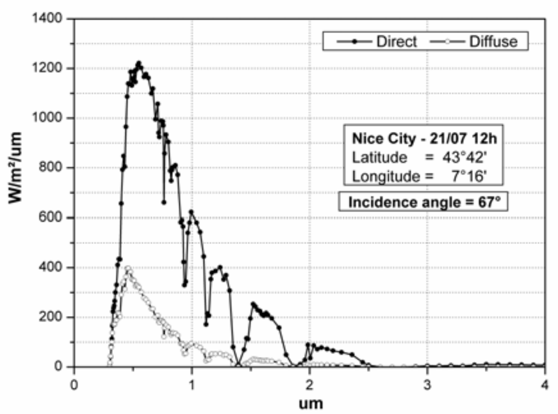

Figure 2 Spectral representation of the direct and diffuse solar radiation (south orientation).

The incidence angle of the direct solar radiation is 67°. The spectral representation presented in figure 2 was computed with SPECTRAL2 developed and validated by Bird (Bird et al. 1984).

The following table gives the quantities of the direct and diffuse solar radiation integrated on four wavelength bands:

Table 3
Solar components according to the wavelength bands (Nice – 21 July at 12h)

BANDS	DIRECT [W/M²]	DIFFUSE [W/M²]
0 – 0.78 µm	452.76	125.64
0.78 – 2.7 µm	366.61	52.45
2.7 – 4.5 µm	7.98	0.80
>4.5 µm	0	0

The external and the internal air temperatures are set at 302 K (29°C) and 298 K (25°C) respectively. Then the external and the internal convective heat transfer coefficients are 10 W/m².K and 2.5 W/m².K respectively.

The external and the internal radiative temperatures are the external and the internal air temperatures (302K and 298K respectively). Then the external and the internal emissivities are set to 0.9.

Concerning the ventilation strategy in the present work, the channel space is mechanically ventilated. The air is coming from and expelled to the outside. The inlet and the outlet are situated respectively on the bottom and the top of the external façade (figure 1). The inlet air velocity is set at 0.10m/s. This value is situated in the range existing in practical cases: 0.10 to 0.15m/s (BBRI, 2004).

MODELING

The quantification of the radiative and convective heat transfer coefficients is done using the temperature and velocity fields inside the channel of the double-skin and using all surface temperatures of each façade component. These fields and surface temperatures are computed using CFD approach combined with radiative heat transfer model.

The CFD approach means that the equations governing the fluid flow inside the double-skin channel are numerically solved for each small volume (mesh) of the computational domain. This latter is represented by the double-skin geometry. These equations are the continuity, the momentum conservation and the energy conservation (see also Safer et al. 2005). The radiation heat transfer modelling consists on the addition of the radiative energy source terms to energy balance represented by the divergence of the radiative flux. The resolution of these equations will define the pressure-velocity and temperature fields inside the channel of the double-skin. The resolution is done using FLUENT 6.0.20 (Fluent, 1998). This CFD tool is a commercial solver based on the finite-volume method and the SIMPLE solving algorithm developed by Patankar (Patankar, 1980).

Turbulence modeling

As the channel of the double-skin is mechanically ventilated and contains an important number of obstacles (slats), it can be assumed that the air flow inside the channel is turbulent. These turbulences generate turbulence quantities and they are injected in the continuity and in the momentum conservation equations.

The "realizable" $k-\varepsilon$ model (Shih et al., 1995) is used in this study for the closing of turbulent Naviers-Stokes equation system. This model constitutes a revised standard $k-\varepsilon$ model (Jones and Launder, 1972) which is widely used in computational fluid dynamics and validated for classical cases of turbulence flows. A bibliographical study concerning the CFD model validation and the turbulence model (the "realizable" $k-\varepsilon$ model) showed that this approach has been extensively validated for a wide range of flows, including the channel with obstacles and layer flows (Shih et al., 1995; Kim et al., 1997; Fluent, 2001). For all of these cases, the performance of the model has been found to be substantially better than the other turbulent models. Finally, the model used satisfies mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows.

Radiative modeling

Modeling the radiation heat transfer serves to evaluate the radiative energy sources. These are injected in the energy balance. For a better estimation of these radiation energy sources, one has to accurately model the global solar radiation and the long wave radiation. The global solar radiation includes the direct and the diffuse solar radiation. The long wave radiation concerns each component of the double-skin facade (internal and external glazing, solar protections).

The balance between the radiative energy emitted and absorbed by each component defines the radiative energy sources:

$$S_{r,\lambda}(x) = 4\pi\kappa_\lambda(x) n_\lambda^2 I_\lambda^0\left[T(x)\right] - \kappa_\lambda(x) G_\lambda(x) \quad (1)$$

Where:

- $S_{r,\lambda}(x)$: Monochromatic radiation energy sources,
- κ_λ: Monochromatic absorption coefficient,
- n_λ: Monochromatic refractive index,
- $I_\lambda^0\left[T(x)\right]$: Emitted monochromatic radiation intensity defined by the Planck function,
- $T(x)$: Local temperature,
- $G_\lambda(x)$: Incident monochromatic power.

The estimation of the radiation energy sources is obtained from the resolution of the Radiative Transfer Equation (RTE). The RTE for an absorbing, emitting and no-scattering media can be written as:

$$\frac{dI_\lambda\left(s,\vec{u}\right)}{ds} = \kappa_\lambda\left(s\right)\left\{n^2 I_\lambda^0\left[T\left(s\right)\right] - I_\lambda\left(s,\vec{u}\right)\right\} \qquad (2)$$

Where:

- $\vec{u}$: Direction vector,
- $I_\lambda\left(s,\vec{u}\right)$: Monochromatic radiation intensity.

The discrete ordinate (DO) method is used to solve the RTE (Vaillon, 1997; Fluent, 1998). The DO method consists on the substitution of the radiation intensity in spatial coordinate into no solid-angle formulation. The RTE is solved for a set of discrete directions. The integrals over directions are estimated by using quadrature formulas. These formulas are done using the Finite-Volume method and are based on control volume approach (Chui et al., 1993).

On the validity of the CFD model

Verification and validation of the numerical model are very important parts of numerical analysis. However, in real design conditions the experimental date are not available, and good representativity of the numerical model has to be assumed, based on some previous results obtained in similar situations. In the detailed numerical studies using CFD's most of errors result from wrong choice of models used to describe physics (e. g. the turbulence) or from wrong discretisation of the simulated domain.

As said before, the turbulent airflow and radiation models used here have already been successfully employed in similar situations.

In this study unstructured meshing was used in order to represent correctly the air flow around the slats of the solar protection in the channel and to ensure a good numerical stability. The meshes were generated using the Delaunay circle test (Fluent, 2001). The number of mesh for both geometrical discretisation and angular discretisation needed to describe the beam radiation were verified by a sensitivity study of the model (Safer et al. 2004c).

RESULTS AND DISCUSSIONS

To show the impact of the solar radiation on the radiative and convective heat transfer, we proceeded to the computation of the velocity-pressure and temperature fields inside the channel for three direct solar radiation configurations:

- Standard weather (cf. § case description) (Incidence angle, IA = 67°),
- Modification of the incidence angle, IA = 23° (the other conditions and especially the flux values are kept unchanged),
- No direct solar radiation (only the diffuse).

For all configurations, the venetian blind is fully open; that means the slat tilt angle is equal to 0.

Velocity and temperature fields

The following figure shows the iso-velocities inside the channel of the double-skin facade:

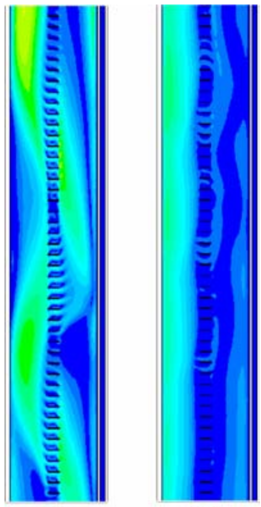

Figure 3 Iso-velocities inside the channel of the double-skin with and without direct solar radiation ((a) and (b) respectively).

Important turbulences due to the direct solar radiation can be seen in figure 3a; the velocity profile is not constant on the height. This induces the mixing of the air between the separated parts of the channel. Without direct solar radiation (figure 3b), the velocity is much more uniform on the height and the air flow is concentrated in the left part of the channel. Nevertheless, the velocity on the right part of the channel tends to zero.

Figure 4 illustrates the temperature profile inside the channel placed at 0.062m and 0.162m from the external glazing for the three configurations mentioned above.

As the velocity field, the same kind of 'oscillations' can be seen in temperature profiles. It can be concluded that the airflow has a major impact on the temperature field inside the channel. In the last case (without direct solar radiation), the air temperature and the slats temperature are uniform and are equal to the outside temperature (302 K). More results are available in Safer et al, 2004a; Safer et al. 2004b.

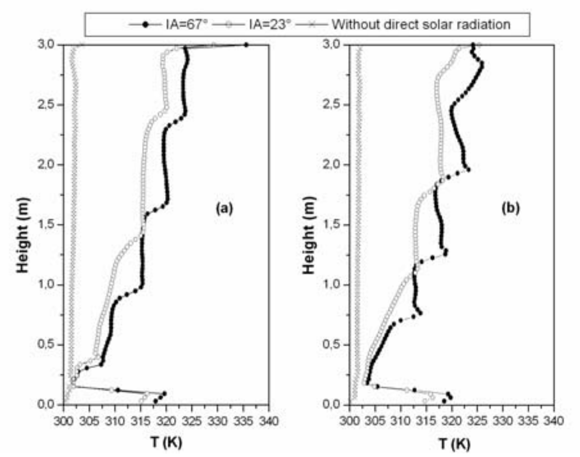

Figure 4 Temperature profiles inside the channel of the double-skin placed at 0.062m and 0.162m from the external glazing ((a) and (b) respectively).

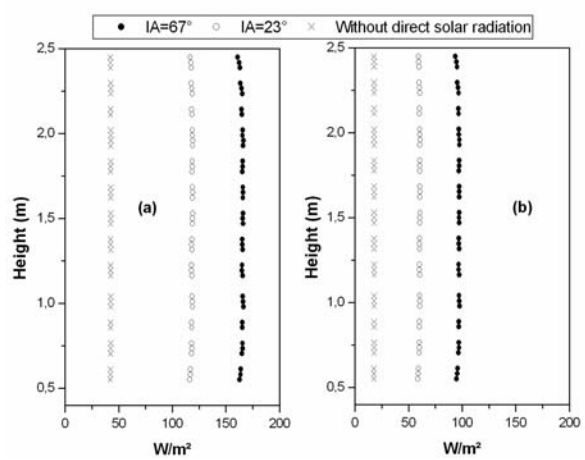

Figure 6 Reflected radiation flux on the external surface for the first band (0 – 0.78 μm) and the second one (0.78 – 2.7 μm) ((a) and (b) respectively).

Radiation heat transfer coefficients

The quantification of the radiation heat transfer consists on the computation of the incident, the transmitted, absorbed and reflected radiation for the internal-external glazing and for the blind. Moreover, the use of the semi-transparent approach allows the quantification of these coefficients.

For the three configurations, the following figure shows the radiation heat flux on the external surface and the transmitted solar radiation to the inside (going through the double-skin façade):

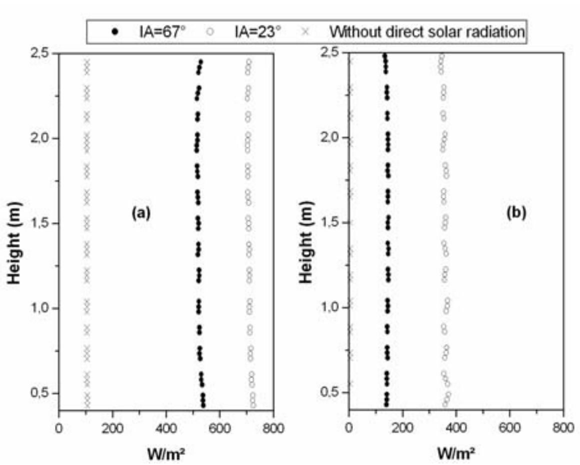

Figure 5 Radiation heat flux on the external surface and the transmitted solar radiation flux to the inside of the building ((a) and (b) respectively).

For the three configurations mentioned above, the figure 6 shows the reflected solar radiation on the external surface relating to the solar bands ((0 – 0.78 μm) and (0.78 – 2.7 μm) respectively):

The radiation heat on the external surface and the solar radiation transmitted to the inside are the most important flux in the second configuration (figure 5). This is due essentially to the incidence angle of the direct solar radiation and to the slat tilt angle of the solar protection. In fact, this tilt angle favors the penetration of the solar radiation to the inside. However, the transmitted solar radiation does not exceed 200 W/m² in the first configuration. Whereas, the reflected radiation is the most important flux in the first configuration (figure 6). This is due essentially to the incidence angle of the first configuration.

In the same way, the quantification of the radiation heat transfer is done for each component of the double-skin façade.

Convective heat transfer coefficients

The computation of the convective heat transfer is done according to the velocity and temperature fields inside the channel.

Table 4
Global model temperatures

TEMPERATURE	WRITTEN
External glazing	*Teg*
Channel between the external glazing and slats	*Tae*
Slats	*Ts*
Channel between the internal glazing and slats	*Tai*
External glazing of the internal double-glazing	*Teig*
Internal glazing of the internal double-glazing	*Tiig*

For our configuration, four convective heat transfer coefficients must be calculated while the global double-skin model is written according to six temperatures (Table 4).

The four convective heat transfer coefficients can be written as:

Table 5
Convective heat transfer coefficients

CONVECTIVE COEF.	WRITTEN
External glazing-air left channel	$hc(eg - ae)$
Air left channel-slats	$hc(ae - s)$
Slats-air right channel	$hc(s - ai)$
Air right channel-internal glazing	$hc(ai - eig)$

A common method to describe these convective heat transfer coefficients uses the Nusselt dimensionless number. This number defines the ratio between the convective heat transfer and the pure conduction.

For our case, these coefficients are directly computed from the following formula:

$$hc = \frac{Qs}{\Delta T} \quad (3)$$

Where:

- Qs : wall convective heat flux,
- ΔT : temperature difference between air fluid (in the middle of the channel) and wall.

The figure 7a and figure 7b show the convective heat transfer coefficients for external glazing-air of the left channel and for the air of right channel-internal glazing relating to the three configurations mentioned below (respectively (a) and (b)).

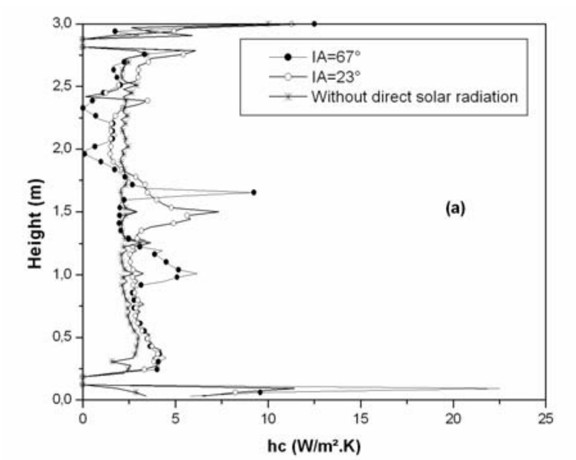

Figure 7a Convective heat transfer coefficient of the external glazing.

In double-skin facade configurations, the convective heat flux is small comparing to the radiation heat flux. The convective heat transfer coefficients are weak and are not too much different from one configuration to another. Nevertheless, without solar radiation, the convection coefficients along the external channel are in the same range compare to other configurations. Concerning the right channel, the convective heat transfer coefficients are not significant (less than 2 W/m²K); this is essentially due to the low velocity inside the right channel.

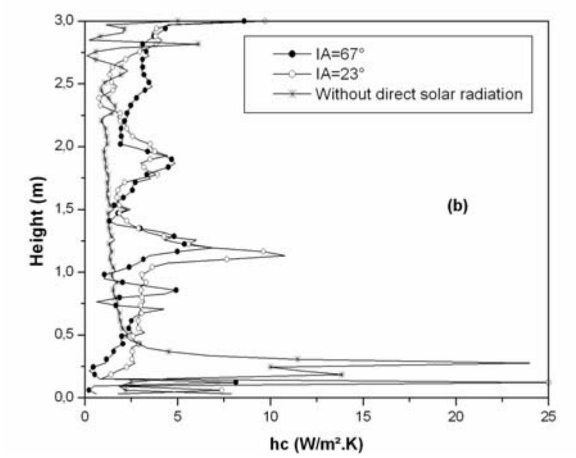

Figure 7b Convective heat transfer coefficient of the internal glazing.

The convective heat transfer coefficients computed within and without solar radiation follow the variation of the velocity filed inside the channel. The convective heat transfer increases with the increasing of the airflow rate inside the channel. Inoue (et al. 1985) cited by Saelens (2002), have experimentally estimated the convective heat transfer coefficients for ventilated channel. The experimental convective heat transfer coefficients were formulated according to the velocities inside the channel. The comparison with these coefficients confirms that our computed convection coefficients are in the correct range of values.

GLOBAL DOUBLE-SKIN MODEL

The main objective of our work is to asses the contribution of double-skin façade to save energy and to limit the overheating problems in summer. The good prediction of the pressure-velocity and temperature fields inside channel and the definition of main influencing double-skin behaviour parameters are our support to design this simplified model. The global model presented in this paper is two-dimensional one; it is based on "n" vertical zones (figure 8). The energy balances are written in each vertical zone.

For each vertical zone, we describe six temperatures as follow:

- Teg temperature: the energy balance is written according to the conduction inside the glazing, to the absorbed radiative energy (solar and infrared radiation for both internal and external surfaces of the glazing), to the heat transfers with the external surroundings and to the convective heat transfer with the air of the left channel,

- *Tai* and *Tae* temperatures: the energy balance is written according to the conduction of the air and to the convective heat exchanges with the closest surfaces (the external glazing-slats and slats-internal glazing respectively),
- *Ts* temperature: the energy balance is written according to the absorbed radiative energy (solar and infrared radiation for both internal and external surfaces) and to the convective heat exchanges with the surroundings (the left and right air channel),
- *Teig* temperature: the energy balance is written according to the conduction inside the glazing, to the absorbed radiative energy (solar and infrared radiation for both internal and external surfaces), to the convective heat exchanges with the external surroundings (the air of the right channel) and to the heat transfers between the panes of the double glazing,
- *Tiig* temperature, the energy balance is written according to the conduction inside the glazing, to the absorbed radiative energy (solar and infrared radiation for both internal and external surfaces), to heat exchanges with the internal surroundings and to the heat transfers between the panes of the double glazing,

Temperatures are computed for each point (figure 8) according to their energy balances defined above. Radiative and convective heat transfer coefficients have been computed for each main influencing double-skin configuration. For example, the slat tilt angle effect on convective heat transfer coefficient is limited. However, it is still an important parameter for the radiative heat transfer coefficients since it regulates the solar radiation transmitted to the inside. For this case, convective coefficients are unchanged; however, radiation coefficients depend on the slat tilt angle. Finally, the global double-skin model takes into account both external weather data and internal surroundings.

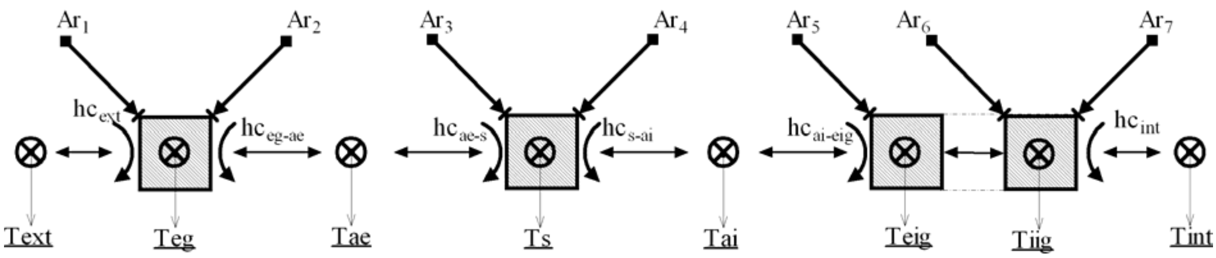

Figure 8 Vertical zone definitions.

CONCLUSION AND PERSPECTIVES

A nodal model, representing thermal behavior of a double skin façade, composed of 6 nodes in the horizontal direction and of n layers in vertical direction was proposed here. Besides conduction, the energy balances in each node include the convection fluxes described by convective heat transfer coefficients and the radiation heat transfer. Results from detailed CFD model were used in order to compute these quantities as a function of the velocity and temperature fields inside the channel of the double-skin.

The results showed that in double-skin facade configurations, the convective heat flux is small comparing to the radiation heat flux. The convective heat transfer coefficients found are weak and are only little influenced by slat tilt angles and solar radiation. They increase with the increasing of the airflow rate inside the channel. The computed values are in agreement with experimental range of values from the literature.

The slat tilt angle effect on radiative heat transfer is very important, since it regulates the solar radiation transmitted to the inside. In the case of fully open blinds the radiation heat on the external surface and the transmitted solar radiation to the inside are logically the most important where the incident angle of solar radiation is small.

The next step of the present work is the implementation of the global double-skin façade model within a building energy simulation code (TRNSYS). TRNSYS tool will be used to simulate the energy performance of a multi-zone building equipped with a double-skin facade. Some comparisons with experimental data regarding the performance of the double-skin facade are planned in order to validate the global model.

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