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NUMERICAL ANALYSIS OF A DOUBLE SKIN FAÇADE WITH INTEGRATED MOVABLE SHADING SYSTEMS

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ABSTRACT

Double skin façades have become an important and increasing architectural element in office buildings as they can provide numerous advantages such as energy saving, sound, wind and pollutant protection with open windows, solar preheating of ventilation air, night cooling and aesthetics.

In the present study, preliminary results of the fluid dynamics behavior of a glass double skin façade equipped with integrated movable shading devices are presented; the aim is to optimize both winter and summer energetic performances. The model is developed for a façade oriented towards the south direction and taking into account the climatic data of Italy.

The double-skin façade constitutes an optical-energetic system with several different layers; therefore, a spectral modelling is necessary, considering that materials have optical properties heavily dependent on wavelength.

A spectrophotometric campaign on glasses and opaque materials has been conducted to evaluate transmittivity, reflectivity and absorptivity of each layer, investigating also their variations with light incidence angle. Optical characteristics constitute the input data for a computational fluid dynamics code, whose task is to model the façade cavity airflow that results from many simultaneous thermal, optical and fluid flow processes, which interact and are highly dynamic. The solar radiation path with its multiple reflections at the different interfaces have been taken into account, employing a ray tracing method, integrated in the CFD code.

The simulation shows that the winter configuration of the proposed façade enhances the solar heat gain, in spite of the presence of shadings, placed however in horizontal position. Heat is stored in the air that flows in the gap and its motion could be driven by mechanical ventilation or by natural convection; buoyancy driven flows resulted difficult to model because of small driving forces that lead to numerical instabilities. Besides, a strong thermodynamic coupling emerged between the air flow through the naturally ventilated double skin façade and the air temperature difference between the cavity and outside.

Solar gains in buildings are desirable in winter-time, but problematic in summer, as they may cause overheating and discomfort; for this reason the external layer remains open in the hot season, giving the air the possibility of escaping from the gap and blocking, at the same time, the solar irradiation by the shading devices, configured with a high tilt angle.

Results from the CFD package show that the air flow in summer conditions, although limited by the absence of the stack effect, contribute significantly to reduce the heat absorbed by the inner pane, so reducing building cooling loads.

NOMENCLATURE

a	[-]	Constant for materials' angular transmittivity
b	[-]	Constant for materials' angular reflectivity
h	[W/m^{2}K]	Convection coefficient
r	[-]	Reflectivity
t	[-]	Transmissivity
T	[K]	Temperature
Special characters		
β	[K^{-1}]	Thermal expansion coefficient
ε	[-]	Dissipation rate emission
Θ	[degrees]	Incidence angle
k	[m^2/s^2]	Turbulent kinetic energy
λ	[m]	Wavelength
ρ	[kg/m^3]	Density
Subscripts		
0		Reference conditions
1		First polynomial coefficient
2		Second polynomial coefficient
3		Third polynomial coefficient
4		Fourth polynomial coefficient
5		Fifth polynomial coefficient
ext		External: towards external air
int		Internal: towards inner rooms
ref		Reference (one for each material)

INTRODUCTION

A double skin façade consists on an external glass surface, a shading system, a cavity filled with air and an insulating double internal glazing, sometimes integrated with opaque surfaces.

The cavity should be ventilated through the air flux driven by the buoyancy effect (natural convection) or by mechanical devices (forced ventilation). The heat carried to the inner rooms is the sum of the energy directly transmitted through the transparent surfaces plus the secondary emission of the inner skin; the latter depends strictly on the radiation absorbed by the whole system.

Apart from aesthetical considerations, the main advantages associated with the double skin façades could be summarised as follow [1]:

- energy saving in winter time: the system works as an active and passive heat regenerator; in the first case, the indoor ventilation air is preheated inside the cavity, so diminishing the energy demand of the air handler. The passive recovery rises from the fact that the air imprisoned in the gap volume becomes warmer than the external air, with a consequent reduction of the wall heat losses.
- Cooling load reductions if a shading system is installed.
- High sound insulation level of the structure.
- Increase of natural ventilation contribution.
- Low risk of condensation on transparent surfaces because of the continuous air movement.
- High level of natural lighting.
- Protection from wind and pollutants.

The investigation on double skin façades heat transfer mechanisms requires the spectral analysis of all the constituting materials, especially if a high variability of optical properties with the wavelength is encountered [2]. Besides, to properly simulate multiple reflections occurring wherever there is a passage between two different means (e.g. air-glass), dedicated techniques such as ray tracing methods have to be implemented.

The fluid dynamics models representative of the air motion inside the cavity result rather complex, involving turbulent and laminar flows, as well as recirculation phenomena [3, 4], apart from the intrinsic difficulty on defining the type of flow (laminar or turbulent). Therefore, the simulation of the system behavior has been realised through a computational fluid dynamics code.

THE DOUBLE SKIN FAÇADE INVESTIGATED [5]

The analysed solution (figure 1) is formed by an external layer made of an integrated system glass - shading device permitting the exploitation of the double skin façades benefits in winter conditions as well as the cooling load reduction derived from the shading system in summer time. The system is effective if the façade is exposed towards the south direction, when the building is located in the northern hemisphere (the opposite occurs in the southern hemisphere).

The summer configuration with open external skin allows a free recirculation between the cavity and the external air, avoiding the undesired overheating effect, typical of double skin façades with fixed configuration [6].

The inner part is made of a standard double glazing with an opaque surface in the lower part.

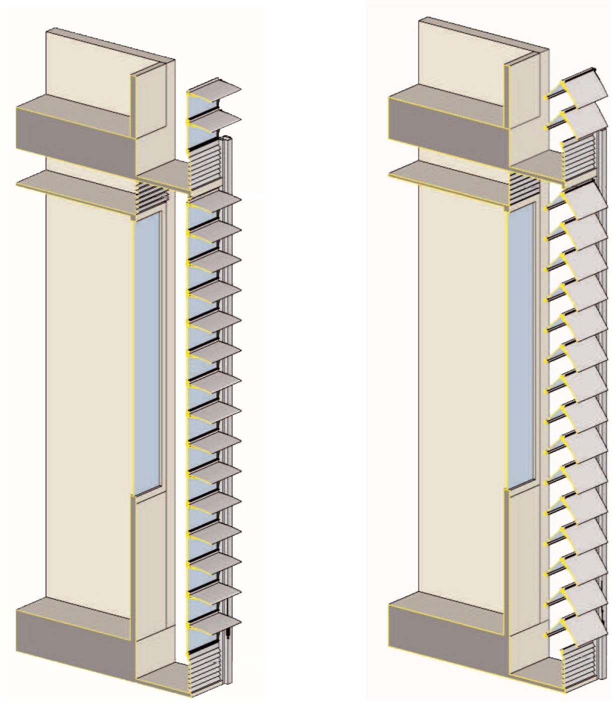

Figure 1 Double skin façade investigated in winter and summer configuration.

SPECTRAL ANALYSIS OF LAYERS'SEQUENCE

The external skin is bounded by a stratified glass (two layers of 5 mm float glass divided by a 0.37 mm film of a plastic material); the shading device is realised by anodized aluminium, an alloy that combines good mechanical resistance properties with a relatively low density and an excellent behavior against atmospheric agents.

The inner skin is assembled with the coupling of the same stratified glass used for the external layer with a 4 mm float glass; the two panes are divided by a 10 mm air gap.

Spectral properties of these materials, obtained by a spectrophotometer Varian - Mod. Cary 2300, are reported in figures 2, 3 and 4.

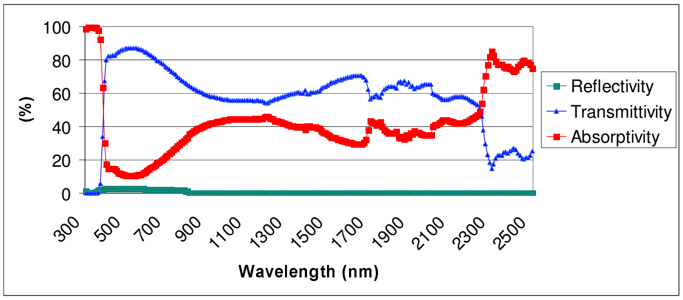

Figure 2 Optical properties of the external skin (stratified glass).

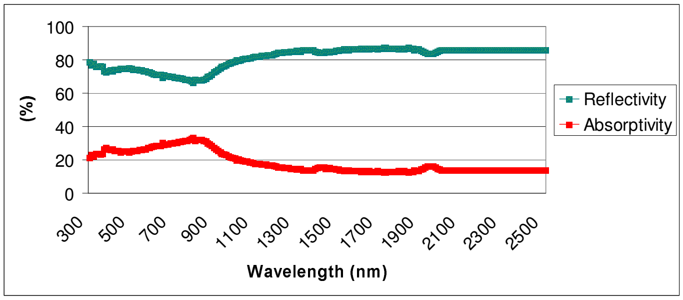

Figure 3 Optical properties of the shading device (anodized aluminium).

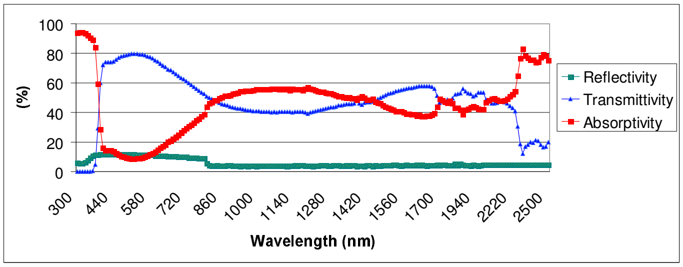

Figure 4 Optical properties of the internal skin (stratified glass, air gap, float glass).

The three graphs show the high levels of glazing transparence, as well as the good reflective properties of the aluminium made shading system.

In winter conditions, this layout permits the entrance of direct solar radiation, together with an indirect contribution linked to multiple reflections on the opaque surface (figure 5).

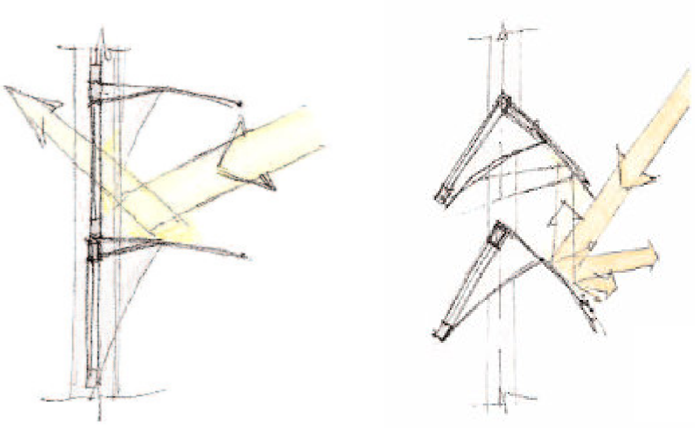

Figure 5 Solar radiation path in winter and summer conditions for the double skin proposed.

In summer seasons, the high reflective properties of aluminium have the effect of sending back the solar rays, because of the high tilt angle of the shading device (figure 5).

Glazing optical properties depend on the incident angle between the surface and the ray direction: as this angle deviates from the normal direction (0°), transmissivity decreases, reflectivity increases, and absorptivity increases.

The variation of optical properties with the incidence angle depends on glass type and thickness; in particular it results more pronounced for coated glass and multiple-pane glazing systems. In the case under investigation, the spectral transmissivity at any incident angle is calculated from the normal angle of incidence, through the following relation [7]:

$$t(\Theta,\lambda)=t(0,\lambda)t_{ref}(\Theta) \qquad (1)$$

where

$$t_{ref}(\Theta)=a_0+a_1\cos\Theta+a_2\cos^2\Theta+a_3\cos^3\Theta+a_4\cos^4\Theta \qquad (2)$$

Similarly, the reflectivity is given by equation (3):

$$r(\Theta,\lambda)=r(0,\lambda)(1-r_{ref}(\Theta))+r_{ref}(\Theta) \qquad (3)$$

where

$$r_{ref}(\Theta)=b_0+b_1\cos\Theta+b_2\cos^2\Theta+b_3\cos^3\Theta+b_4\cos^4\Theta \qquad (4)$$

The spectrophotometric campaign showed a good agreement between experimental data and values derived from equations (1) and (3).

COMPUTATIONAL FLUID DYNAMICS MODEL AND BOUNDARY CONDITIONS

The core of heat transmission has to be found on the air motion inside the cavity; in the hypothesis of free convection, the flux is driven by buoyancy forces. This phenomenon is described by equations of mass, momentum and energy conservation, together with the turbulent flow variables'definition.

The time averaged momentum equation is written starting from the Reynolds form, enriched by an additional term derived by the traditional Boussinesq approximation [8], representing the coupling between temperature gradients and velocity in natural convection. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation [7]:

$$(\rho-\rho_0)g\approx-\rho_0\beta(T-T_0)g \qquad (5)$$

where ρ_0 is the (constant) density of the flow at the operating temperature T_0 and β is the thermal expansion coefficient.

The most commonly used model to simulate the air motion in double skin façades cavities is the renormalisation group k-ε model [9]; therefore, the choice has been addressed towards this method. In the segregated solver used for the calculation, the solar ray tracing model is not a participating radiation model, thus the radiative heat exchange has been taken into account through the P1 model [10].

The analysed façade front surface is 2 meters wide and 3 meters high; the cavity has a width of 0.5 meters. An unstructured mesh of 2,000,000 nodes was defined, being necessary to include not only the space between the two skins but also a volume of external air to implement the solar ray tracing (figure 6).

The façade is south oriented (north if the austral hemisphere is considered) and all simulations were executed in steady sate conditions.

Referring to figure 6, boundary conditions for the winter configuration should be resumed as follow: the external wall is exchanging heat with a convection coefficient h chosen according to the European standards for building design [11] (h_{ext} = 25.0 W/m^{2}K); the external temperature, as well as the solar radiation in the vertical plane, is a function of the day time and the site: their values for each simulation were fixed according to the Italian standards [12], choosing the 15th February in Rome - Italy (figure 7).

Focusing the attention to the indoor heat exchange, it is assumed that inner rooms remain at 20°C, while the adduction coefficient is considered equal to h_{int} = 7.7 W/m^{2}K [11]; indoor and outdoor temperatures were also used in the radiation exchange model.

The upper and lateral walls are considered adiabatic and they do not participate to the solar ray tracing; surfaces outside the double skin and the opening in the upper internal wall were given respectively an inlet and an outlet pressure boundary conditions, with a value of 101,325 Pa.

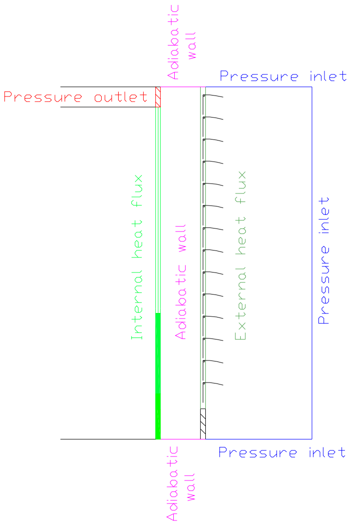

Figure 6 Definition of boundary conditions.

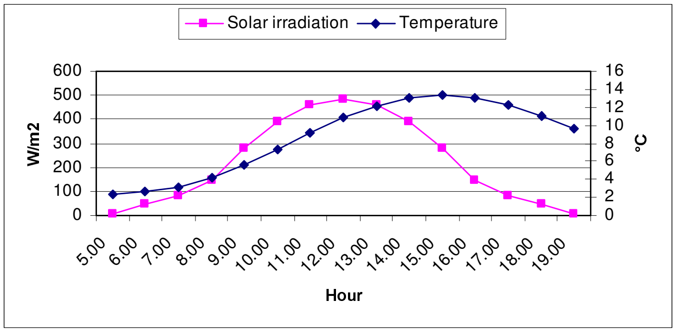

Figure 7 Climatic data of a winter day (15th February) in Rome.

RESULTS

The instauration of natural convection inside the gap is evident from figure 8.

In figure 9 a graph of three simulations implemented for the city of Rome in the chosen day (15th of February) is reported: the solar incident radiation in the vertical plane is sketched, together with the radiation transmitted through the double skin façade into the inner room. It is also added the trend of the outlet temperature and the temperature difference between the gap and outdoors: the latter value constitutes the most important parameter to assess the double skin performance because it represents the effect of the "air buffer", the actor that gives a better insulation of the façade. The higher this value, the lesser will be the heat dispersion through the building external walls.

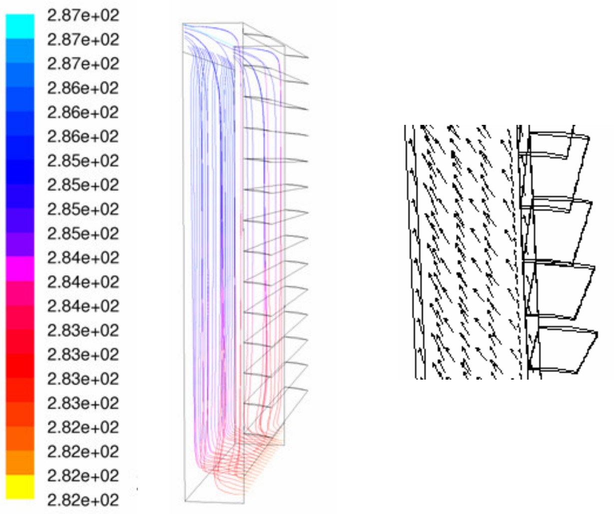

Figure 8 Path lines coloured by static temperature (K) and detail of velocity vectors in the configuration relative to Rome, 15th of February, at 08:00.

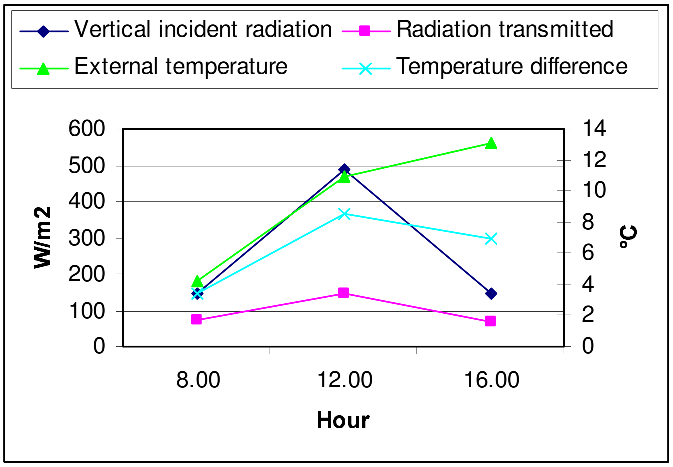

Figure 9 Façade performance in Rome, winter conditions.

It is evident that, although the solar radiation presents a peak in the middle hours of the day, the particular configuration of the shading system permits the passage of only a short percentage of the total flux, because of the elevation of the sun above the horizon. On the other hand, in the morning and in the afternoon, the limited value of solar radiation is compensated by the low sun elevation.

The final effect is evident through the temperature difference between the gap and the external environment: the trend follows the radiation transmitted and it seems independent by the external temperature. Therefore, the solution effectiveness is strictly linked to the capacity of capturing the solar radiation by glass transmittivity and multiple reflections of shading surfaces.

The shading system opening in the hot season, as showed in figure 10 relative to a typical summer day in Rome at 12.00, limits significantly the solar radiation input to the building; the consequence is a considerable reduction of the cooling load.

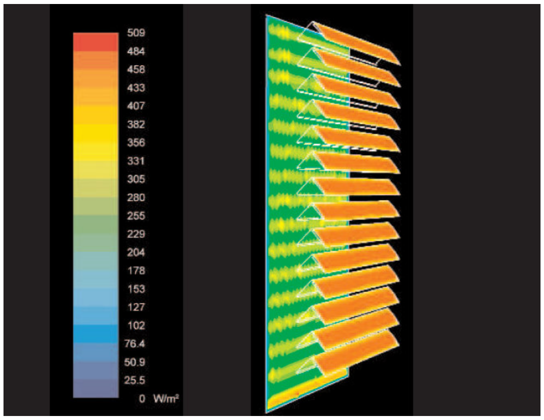

Figure 10 Transmitted solar heat flux (W/m^2) in summer conditions.

The overheating effect that could rise in summer conditions inside the double skin façades with closed configurations is avoided by the communication between the gap and the external air. As showed in figure 11, air recirculation appears through the outer skin, guaranteeing a ventilation flux that keeps the air temperature at values close to external conditions.

Being the shading surface exposed towards the sun, it is possible to substitute the aluminium with photovoltaic modules, so increasing the energetic performance of the façade [13].

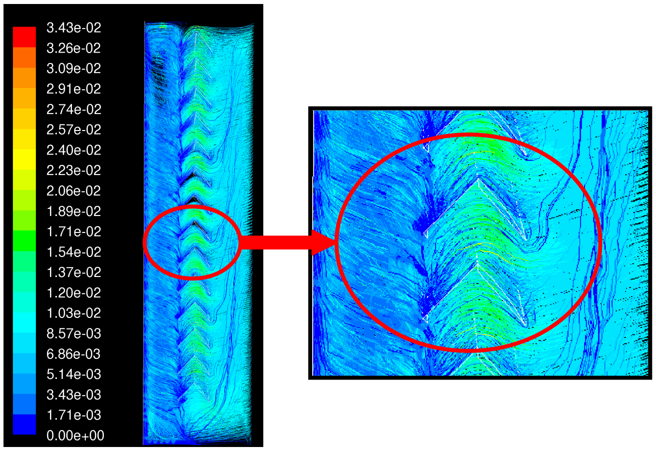

Figure 11 Path lines coloured by velocity magnitude (m/s) in summer conditions.

CONCLUSION

The preliminary study of the fluid dynamics behavior of a new type of glass double skin show an optimized behavior both in winter conditions as well as in the hot season, where traditional double skin façades present weak performances because of the gap overheating. The energetic analysis pointed out the strong effect of the spectral properties of each component: the high reflection shading device allows good solar gain in winter and cooling load reduction in summer.

The simulation of façade performances with a CFD model showed for the winter configuration (shading closed) the instauration of a buoyancy induced flow inside the gap, producing the double beneficial effect of diminishing the heat dispersion through external walls and preheating the air for ventilation purposes. These effects depend more on the amount of captured energy than on the absolute value of incident solar radiation. Summer simulations show a good behavior of the system because of contributions of the high shading level and the open configuration that inhibits the overheating.

The future work should deal with the extension of simulations on different sites, with a higher number of hours investigated each day and assessing the performance of the façade proposed with the variation of geometric parameters such as the gap depth and the shading tilt. It will be also useful to prosecute the analysis in unsteady conditions at the aim of considering the quick variation of climatic conditions outside the building.

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