HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

THERMAL AND ENERGY ANALYSIS OF DOUBLE-SKIN FAÇADES

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ABSTRACT

The use of double-skin glazed façades and other façade cladding, forming the so-called ventilated chamber, has been extended nowadays as bioclimatic building improvements. Double façades are constructed to allow ventilation in buildings and to prevent noise from outside but have as well a significant influence on their energy consumption. In the present work an experimental setup was carried out with two enclosures of insulating walls, one with a single glass façade and the other one with double glazed façade with a ventilation air chamber. Some of the values of the global inner temperatures and solar radiation measured on the experimental setup for the most representative days are presented. It is found that the internal temperatures are clearly different on both setups in the period of higher irradiation. Experimental measurements taken along several months show a temperature difference between both configurations ranging from 5ºC to 10ºC.

A finite element simulation has also been performed in transient regime to analyze the thermal behavior of both cells. The experimental results and those obtained through simulations are in good agreement in terms of temperatures. The numerical simulation provides also the heat flux exchanges taking place in the modeled cells. The associated energy analysis shows an impact on the energy saving of the building of about 20%.

INTRODUCTION

Double façades are constructed to allow ventilation in buildings and to prevent noise from outside. The double glass façades are composed of two glazed skins and a cavity between them. The intermediate cavity basically works as an isolation and storage area to reduce heat losses when it is closed, but also acts as an effective ventilation channel when is opened at both ends, thus higher thermal advantages can be achieved both in summer and winter. Among the advantages of ventilated façades, we can mention: optimization of indoor thermal control through the air between the two enclosures, reduction of noise level, increasing weather protection, possibility of night ventilation and fire protection. Among the disadvantages are: increasing of manufacturing and cleaning costs.

Nowadays there is a great interest in the development of sustainable construction worldwide and saving energy in buildings. To reduce the amount of energy consumed by HVAC systems without affecting the interior thermal comfort is then necessary to study the impact and optimize the design of façades. The effectiveness of double façades in reducing buildings energy consumption is conditioned by several factors as the environmental variables (external temperature, humidity, solar radiation and wind) and building characteristics (orientation, optical properties, etc). Economic factors affecting the cost of the façade must be also considered and include maintenance costs, energy, cleaning and repairs [1]. Some studies on natural ventilation in high rise buildings with double façades improvements have pointed out the energy saving and costs [2, 3].

It is also frequent to install a blind inside the air chamber or solar protection elements, which allows to vary the solar factor, the luminous transmission, the surface temperature or the coefficient of thermal transmission, since the outer glass envelope is fixed. Configurations based on fin arrangements inside the gap [4] or thermal diode type cavities [5-7] have been proposed to enhance or reduce the convection heat transfer from the building selecting the most favorable configuration for each season.

The numerical analysis by means of CFD including convection, conduction and radiation, is a powerful tool that allows us to visualize the dynamics of the fluid flows and the energy exchanges taken place in ventilated façades and its influence on the indoor conditions. In [8] a study of double façades with natural ventilation is performed and the temperature profile in the ventilation duct of a three-story building is analyzed, indicating the thermal envelope improvements for energy savings.

In a previous work [9] we have analyzed several types of glass façades through CFD simulation of a basic module of dimensions $3x3x3m^3$. The results for configurations with double glass façade indicate energy savings of about 20% compared to the case of a simple façade.

The current work presents the results for the simulation of heat transfer in enclosures equipped with double and simple façades together with measurements taken on small scale, purpose-built cells. The experimental setup consist of two cells made of insulation panels, the first one with a single glass façade and the second one with double glazing and air chamber, to play a double ventilated façade.

EXPERIMENTAL SETUP WITH THERMAL CELLS

In order to experimentally verify the results on energy exchanges obtained by simulation of different configurations, two reduced-scale enclosures were built using insulating panels of 4 cm thick of extruded polystyrene. The dimensions of both enclosures are $1.0x0.5x0.6m^3$, the first one with a single glass façade of 6 mm in thickness and the second one with double front glass cover, being the two glasses separated 7 cm to play a double ventilated façade, with upper and lower openings which allow the air to pass between them (Figure 1). Temperature at selected points is measured with an accuracy of ± 0, 5ºC using a set of sixteen K-type thermocouples of 0.5 mm.

The instrumentation used for temperature acquisition are three data logger OPUS 208 with digital and analog I/O which allow to take data simultaneously in 24 channels with a sampling time of 0.01s

The incident radiation on the vertical surface of the façades is also measured by means of a calibrated photovoltaic cell, with a calibration constant of 100 mV /1kW/m^2) ± 2.2%.

The configuration of the input ports and sensors is made with the Smart Control 1.5 software connected to a laptop used as well for later graphical and statistical treatment of the data.

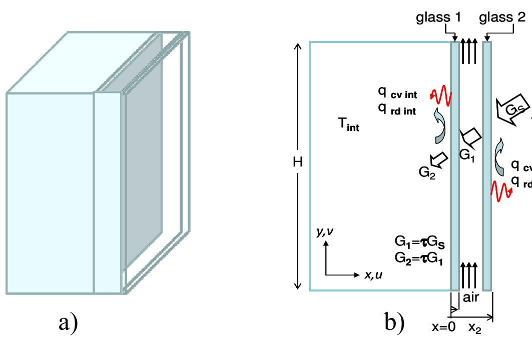

Figure 1. a) Sketch of the double glazed cell. b) 2D model used for the double glazed cell.

The 16 thermocouples are arranged on different points of the inner and outer façades, 6 thermocouples in the first cell and 10 others in the second. Inner and outer ambience temperatures were also registered. A variant of the experimental setup consisting of cells with opaque lower-half façades was also monitored in order to study the effect on the overall performance. For this purpose an opaque cover is superimposed in the lower part of the double glass façade.

Earlier measurements were made on these prototype cells to adjust the measurement process, calibration of sensors and tuning of the entire system. The cells were situated in the flat roof of the laboratories of the Industrial Engineering School in Madrid and continuous measurements were conducted along the months of September through December 2011.

EXPERIMENTAL RESULTS

Some of the values of temperature and solar radiation measured on the described experimental setup are shown in Figures 2-4. The most representative days of stable weather have been selected for presentation. Although 16 different temperatures were individually tracked, for the shake of simplicity only the inner mean temperatures are plotted in the graphics. A detailed comparison of the whole set of temperatures at different wall locations will be presented in an extension of the present work. The main features that can be drawn from the collected data are:

- The characteristic daily cyclic variation of temperatures is seen in the experimental data for the different days.
- Maximum measured values of solar irradiance for clear days in October are about 1000 W/m^2
- The temperatures reached inside the cells are quite high, between 60°C and 70°C, corresponding to the values expected in the absence of air-conditioning system.
- The inner temperatures in both cells are clearly different between them in the period of higher irradiation, being consistently higher in the cell with a single glass. Differences of 5ºC in the measured inner temperatures are usual when the outer ambience temperature is about 27ºC. These differences can be up to 10 ºC for other values of outdoor temperature and higher solar radiation.
- Even in days with changing weather conditions, there is a trend in the temperature of the double-façade cell to be lower than that reached by the cell with single façade.

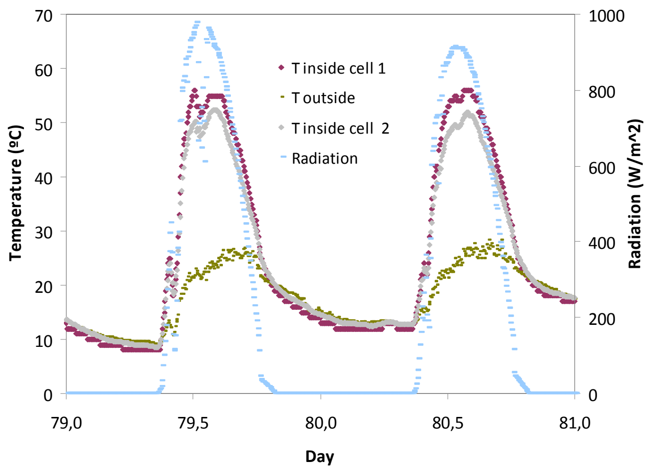

Figure 2. Data of temperature for the 21st and 22nd of October

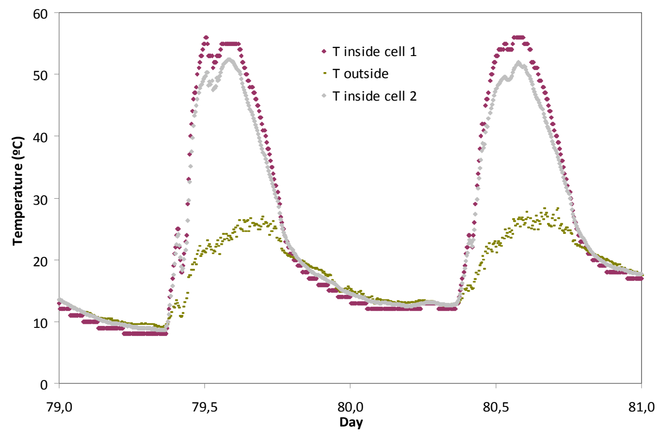

Figure 3. Data of temperature and radiation for the 21st and 22nd of October

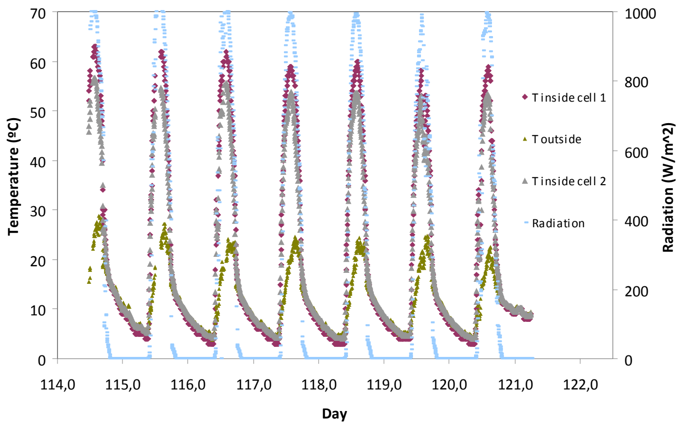

Figure 4. Data of temperature and solar radiation for November 25th to December 1st

THERMAL SIMULATION OF THE CELLS USING CFD

The geometry of the treated double cell is sketched in Figure 1. The single glazed enclosure is the same but without glass 2. The problem discussed involves the combination of the three heat transfer mechanisms, taking radiation and convection a prominent role. The cover glasses are considered as a semitransparent media on which the incident solar radiation is partially transmitted to the interior. Several variables and parameters have effect on the final inner temperature reached by the cells and should be taken into account in the model.

External conditions outside the cells:

-Temperature and atmospheric pressure.

- Solar radiation: intensity and direction of solar irradiation at different instants.

Conditions inside the cells:

- Initial inner temperature and velocity of the air

Geometrical parameters:

- Dimensions of the cells and ventilation channel
- Thickness of the glazed surfaces.

Thermophysical and optical properties of the intervenient media:

-Thermal conductivity, density and specific heat for solids and fluids, plus viscosity of the air

- Emissivities, transmission and absorption coefficient of the glass and solid walls.

The governing equations for the 2D, incompressible flow inside the cells and on the vertical channel are

$$\begin{cases} \dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial y}=0 \\ \rho_0\left(\dfrac{\partial u}{\partial t}+u\dfrac{\partial u}{\partial x}+v\dfrac{\partial u}{\partial y}\right)=-\dfrac{\partial p}{\partial x}+\mu\left(\dfrac{\partial^2 u}{\partial x^2}+\dfrac{\partial^2 u}{\partial y^2}\right) \\ \rho_0\left(\dfrac{\partial v}{\partial t}+u\dfrac{\partial v}{\partial x}+v\dfrac{\partial v}{\partial y}\right)=-\dfrac{\partial p}{\partial y}+\mu\left(\dfrac{\partial^2 v}{\partial x^2}+\dfrac{\partial^2 v}{\partial y^2}\right)-\rho_0 g\beta(T-T_0) \\ \rho_0\left(\dfrac{\partial T}{\partial t}+u\dfrac{\partial T}{\partial x}+v\dfrac{\partial T}{\partial y}\right)=\dfrac{\lambda}{c_p}\left(\dfrac{\partial^2 T}{\partial x}+\dfrac{\partial^2 T}{\partial y}\right) \end{cases} \quad (1)$$

where u, v are the Cartesian components of the velocity, ρ_0 is the reference density, p is the pressure, g is the acceleration of gravity and λ, c_p, μ and β are the conductivity, specific heat, viscosity and expansion coefficient of the air respectively.

Within the glass (semitransparent wall), the equation of temperature distribution is

$$\left(\frac{\partial^2 T_g}{\partial x^2}+\frac{\partial^2 T_g}{\partial y^2}\right)-\frac{1}{\lambda_g}\frac{\partial A(x)}{\partial x}=\frac{\rho_g c_{pg}}{\lambda_g}\frac{\partial T_g}{\partial t};\quad A(x)=G\exp(-\alpha_g(w-x)) \quad (2)$$

where subindex g refers to glass properties, G is the incident solar radiation (G_S for the outer glass and G_I for the inner one), w is the thickness of the glass and α_g its extinction coefficient.

The boundary conditions of the problem are:

-continuity of heat fluxes at glass-ambient interface

$$-\lambda_g\frac{\partial T_{g2}}{\partial x}=\sigma\varepsilon_g(T_{g2}^4-T_{ext}^4)+h_{ext}(T_{g2}-T_{ext}) \quad \text{at} \quad x=x_2,\ 0\le y\le H$$

$$-\lambda_g\frac{\partial T_{gl}}{\partial x}=\sigma\varepsilon_g(T_{gl}^4-T_{int}^4)+h_{int}(T_{gl}-T_{int}) \quad \text{at} \quad x=0,\ 0\le y\le H \quad (3)$$

-continuity of heat fluxes at wall-ambient interface

$$-\lambda_w\frac{\partial T_w}{\partial n}=\sigma\varepsilon_n(T_w^4-T_{ext}^4)+h_{ext}(T_w-T_{ext})$$

- no-slip condition (u=0, v=0) at walls of the ventilation channel and at inner walls

-Initial conditions: velocity is zero everywhere and T_0= T_{ext}

A study on transient state was undertaken to obtain the inner temperatures of the cells, considering the changing conditions of ambient temperature and solar radiation over a typical day. Values for one of the days, the 22nd of October, have been taken as representative and used to reproduce through simulation the temperatures expected in each cell for different times. Simulations have been performed using the CFD code ANSYS-

FLUENT [10]. The number of mesh elements is 5142 for the cell with single glass and 8804 for the double-glass cell, with much more finer elements near the walls and in the channel in order to properly consider the proximity effects. Different tests were carried out to found mesh–independent solutions. Turbulence is modeled by the standard *k–ε* model and radiation exchanges by the discrete ordinate model. The governing equations were solved by using the segregated method and the SIMPLEC algorithm is used for the pressure–velocity coupling. Second order schemes are considered for the resolutions of mass, energy, momentum and pressure equations. The convergence is considered attained when the difference between two successive iterations is less than 10^{-4} for velocity components and 10^{-7} for the energy equations. Several tests were also carried out to check that 2D models provide essentially the same thermal results than 3D simulations but with a significant computing time saving. The temperature and velocity distributions were calculated in transient regime with varying boundary conditions given that the outer temperature and solar radiation are changing along the day. The reference

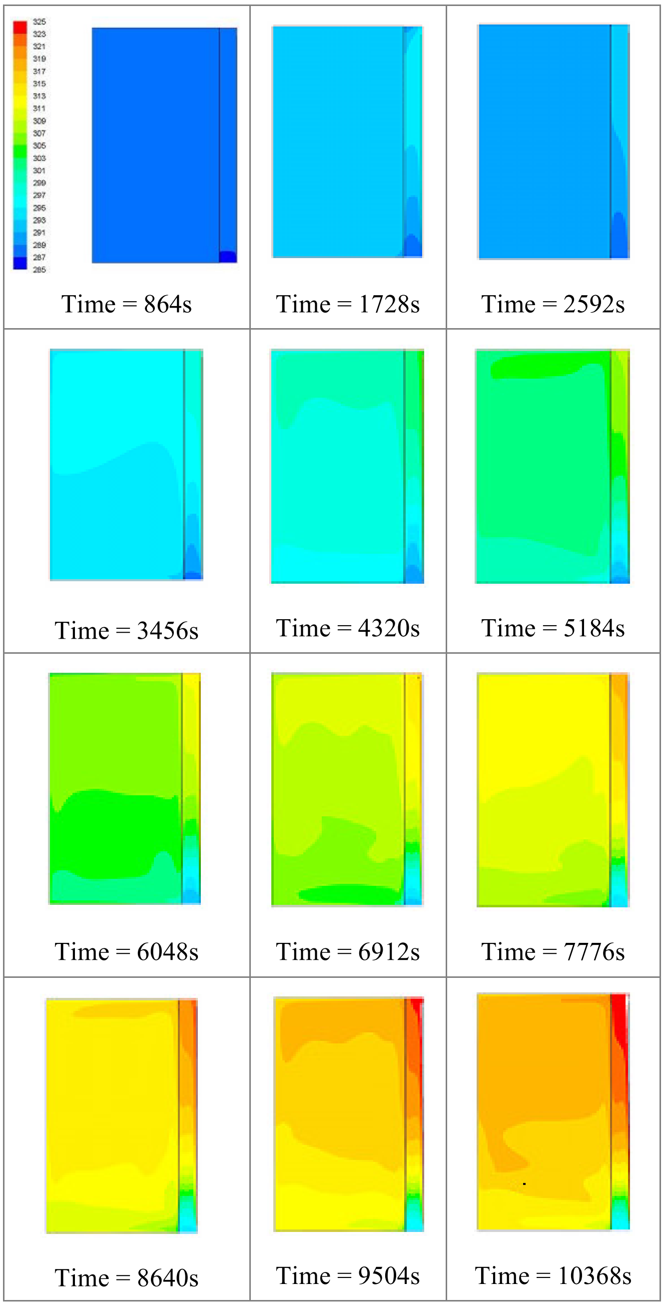

Figure 5. Cell with double façade. Simulation of the temperature evolution

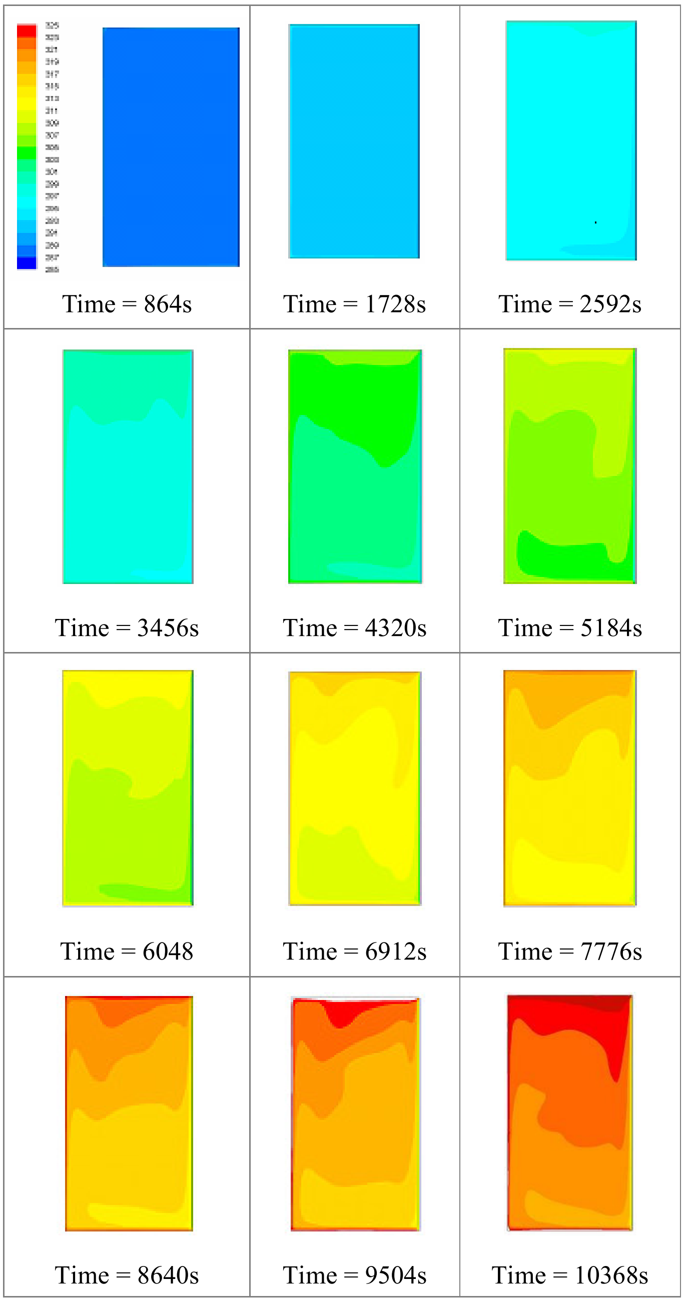

Figure 6. Cell with single façade. Simulation of the temperature evolution

time step taken is 0.01 days (864 s), although basic steps of 32 s are used for the convergence process. Fields of temperature and velocity obtained for each reference time after convergence are used as the initial conditions for the next time step when the boundary thermal conditions change. Main results are condensed in Figures 5 and 6, being the process to obtain the whole set of images very laborious and highly time consuming.

It can be seen from Figures 5 and 6 how the inner temperatures increase as a function of time, as expected, and that the air flow in the ventilation channel intensifies due to a more intense natural convection as the solar radiation increases along the morning of the day (cells were oriented to the South). This air flow in the channel notably modifies the heat exchange of the enclosure and is the final responsible of the inner temperature distribution reached by the double façade cell which is substantially different from the single one in the moments of higher solar radiation.

The difference of the average inner temperatures between both cells are essentially null at the beginning of the day but they gradually increase up to a maximum which is reached at about 14:00h (LCT) coinciding with the maximum of solar irradiation, while the maximum of the outer temperature is registered about one hour later. For that day, the maximum temperature in the interior of the double cell is 49ºC while for the simple cell is 57º C. Obviously the hot air is concentrated in the upper part of the cell in both cases. The numerical results provide also the dynamics of the internal air flow and its evolution in time. It is found that, once the cavities start to be heated, air flows downwards on the inner side of the glass and upwards on the back wall of the cell in both cells. As for the ventilation channel of the double-façade cell is concerned, the air is quiet at the beginning but the natural convection progressively increases up to reach stable values of the velocity that are close to 0.1 $m \cdot s^{-1}$. At that time, the air entering by the lower part of the channel at 26ºC exits at about 58ºC. The velocity of the air in the channel reaches the maximum close to the surface of the outer glass, in the upper part of its inner face. Then, the external thermal load due to radiation is not fully transferred to the interior of the cell and is partially taken away by the induced air circulation. This fact can be advantageously used in buildings with a high radiation load due to the orientation of their glazed façades. The effect is clearly perceptible in terms of temperature.

COMPARISON OF THE EXPERIMENTAL RESULTS WITH SIMULATIONS

Table 1 summarizes the data of measured and calculated inner temperatures for both cells corresponding to the morning of October 22. The maximum difference of measured temperatures in both cells is 5.3 ºC. For other cloudless days of the monitoring period, the experimental temperatures inside show similar trends but differences can be larger (as much as 10ºC) depending on the solar irradiation and the ambience temperature.

On the other side, the concordance between the temperatures measured on the experimental setup and those obtained through numerical simulation is quite satisfactory, being the discrepancy below ±2ºC. A direct comparison of these temperatures can be seen in Figure 7 where the experimental temperatures are plotted together with the calculated values obtained by numerical simulation for the indicated date and times. Such agreement comes to validate the numerical model and allows to use this model to obtain further information on the heat exchanges that otherwise are not easy to acquire experimentally. It is the case, for example, of the heat fluxes exchanged by combined convection and conduction across the walls of the enclosure or by combined radiation, conduction and convection in the semitransparent glass. Changing the boundary condition to a given temperature for the walls of the cells (that is compatible with comfort conditions) and keeping the condition of variable solar irradiation on the glazed façade, it is possible to calculate the thermal load in both types of cells and hence the difference in energy consumption of the refrigeration (or heating) system.

New calculations have been carried out by considering a temperature of the walls of 25ºC that will limit the temperature of the inner air to the range 25-26ºC. Figure 8 shows the net heat flux entering the single-glass and the double-glass cells calculated for the given conditions on October 22. The thermal load is noticeably higher for the single cell in the central part of this cloudless day, what results in greater refrigeration demand. This thermal load is however positive in seasons where the heating system is needed. The double glazed façade could then be seeing as counterproductive because the natural convection will cool the building. A modification of the configuration for this case by simply closing the ends of the vertical channel will provide an additional isolation chamber which diminishes the heat losses with respect to the single glass façade. This effect is clearly observed both in our numerical model and in the experimental setup when the channel is closed.

Table 1. Calculated and measured temperatures on the cells

	Cell with double façade		Cell with simple façade	
Day	T simulation(ºC)	Tmeasured(ºC)	T simulation(ºC)	Tmeasured (ºC)
80,37	13,25	13,0	13,25	13,0
80,38	14,75	15,5	16,45	15,5
80,39	17,25	18,0	20,65	18,0
80,40	19,15	21,0	22,85	22,0
80,41	22,65	24,0	26,85	25,0
80,42	25,85	27,0	30,85	29,0
80,43	29,35	30,0	34,85	32,0
80,44	32,75	33,0	37,45	36,0
80,45	35,85	37,0	39,25	40,0
80,46	38,35	39,0	41,85	43,0
80,47	41,05	42,0	44,85	46,0
80,48	43,55	44,5	48,65	49,0
80,49	45,55	46,0	48,55	51,0
80,50	47,05	47,7	50,65	53,0

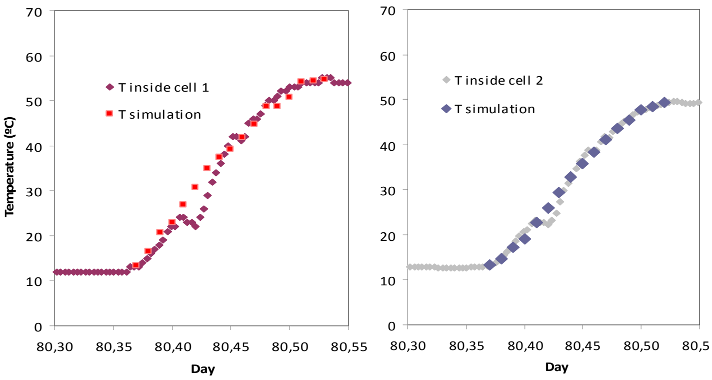

Figure 7. Measured and calculated temperatures along the morning of the 22nd of October: a) cell with single façade, b) cell with double façade

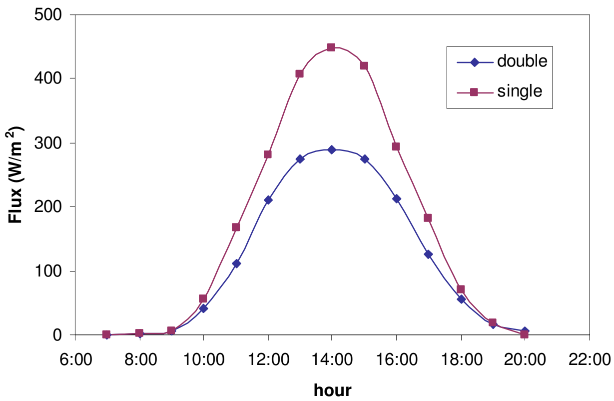

Figure 8. Net heat flux entering the cells, calculated by numerical simulation on the 2D model, at site ambient conditions on October 22.

CONCLUSION

The effect of a double glazed ventilated façade on the thermal behavior of a building has been analyzed both numerical and experimentally. Temperatures on two experimental cells exposed to external weather conditions have been monitored for several months. These thermal cells, one equipped with a double glass vertical cover acting as a ventilation channel and the other one with a single glass cover, were also modeled using CFD to characterize the natural convection and combined heat transfer fluxes taking place in each case. The problem is analyzed in transient regime given that solar radiation and the ambient temperature change along the day. The transient temperature and velocity distributions have been obtained through numerical simulation providing useful information on the features of the internal and channel air flows. The evolution of the calculated mean temperatures in the interior of both cells is compared with the experimental values taken in a typical day. The agreement between these values is very good, with small differences in the range of ±2ºC. The experimental measurements reveal that the differences in the inner temperatures of both cells can reach up to 10ºC depending on the ambient temperature and the solar irradiation. An estimation of the entailed thermal load for each cell based on the computed heat fluxes is also presented.

A detailed comparison of the temperatures simultaneously taken in selected locations of the glazed façades will be extensively compared with the numerical calculations in a future work with the aim of providing a further validation of the numerical 2D model used. The analysis of the fluid dynamics and heat fluxes for different constructive configurations is of great interest to optimize heat transfer and to support energy-efficient solutions for buildings.

Acknowledgements

This work has been partially supported by UPM under research grant No. Q10-5607170.

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