IMPROVING THE WHOLE BUILDING MODELLING AND INTEGRATION OF AN INNOVATIVE WINDOW USING THE PASSYS TEST CELL

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ABSTRACT

The SOLVENT window is an innovative glazing system concept that involves the use of a rotating frame, an absorptive glazing and a naturally ventilated vertical channel, in order to improve the balance between the visual comfort and the energy efficiency of windows.
The tools available for simulating the behaviour of the window in terms of visual comfort and of thermal and energetic behaviour are complex and potentially dependent on many calibration parameters, such as, for example, the heat convection coefficients or the number of nodes in an air flow network. Different modelling approaches can lead to large variability in the results obtained. It is thus essential that the models must be supported by measurements that may, on one hand, help to optimise the component modelling and, on the other hand, assure that the global results provided by the model are realistic.
In the case of the SOLVENT window, a prototype mounted on a PASSYS test cell in Porto (Portugal) played a fundamental role in this process. The monitoring results were used to: (a) Assess the quality of the results obtained with a base case model; (b) develop improved models for the air flow and for the heat convection in the vertical air channel; (c) Validate the results for the global heating and cooling loads obtained with the optimised model; (d) Calibrate the parameters needed for accurate daylighting simulation with Radiance.
Once the component model was optimised and validated, it was then applied in realistic global building models for detailed performance studies. An example is provided for the virtual application of the SOLVENT window to an office in Porto, Portugal.

Keywords: Windows, Natural Convection, Vertical Channel, Daylighting, Energy, Building Simulation

1. INTRODUCTION

The use of clear glazing in buildings has often the goal of capturing solar radiation and providing an unobstructed view towards the outdoor environment. However, it is frequent that the solar radiation entering through the glazed elements of the façade causes visual and /or thermal discomfort to the room occupants. When the room occupants feel a sensation of glare, they usually activate existing solar radiation protective devices such as interior or external blinds. Often, the daylighting illuminance perceived after the activation of blinds is not enough and electric lights are turned on. Even when solar protective devices are not present or are not activated, it is also frequent to verify that the room occupants turn on electric lighting to reduce the sensation of glare produced by the windows. The initial objective of reducing energy consumption for heating and lighting may thus be jeopardized by fewer solar gains and by an increased demand of electricity for lighting.

In an attempt to reduce the problems of visual comfort caused by the use of clear glazing, but at the same time keeping its energy-saving advantages, Yair and Etzion proposed a new concept of glazing system, henceforth called the SOLVENT window [1]. The new concept consists essentially of a common double clear glazing plus a layer of absorptive glazing placed at a few centimetres away from the clear glazing. The air gap between the two glazings is left open at the bottom and at the top, thus forming an air channel. This window is placed in a special frame that allows the absorptive glazing to be at the outdoor side in Summer mode and at the indoor side in Winter mode [2]. As the absorptive glazing heats up by the effect of solar radiation, a buoyancy-induced flow is created in the air channel. The heat carried by the air circulating in the channel is released towards the outdoors in Summer mode and towards indoors in Winter mode (figure 1).

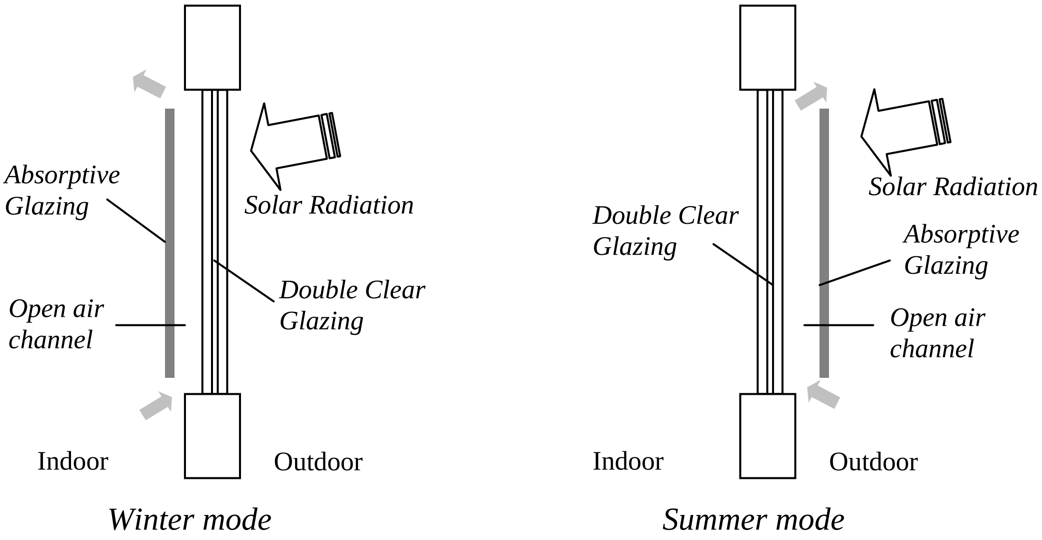

Figure 1. Concept of the SOLVENT glazing system.

In order to select the optical properties of the glazing system and to evaluate the energy and visual comfort benefits that may arise from the use of this glazing system, it is necessary to model it within appropriate building simulation tools. The available tools for accurately simulating the behaviour of the window, in terms of visual comfort and of thermal and energetic behaviour, are complex and potentially dependent on many calibration parameters, such as, for example, the heat convection coefficients or the number of nodes in an air flow network. It is thus essential that the models must be supported by measurements that may, on one hand, help to optimise the component modelling and, on the other hand, assure that the global results provided by the model are realistic.

2. EXPERIMENTAL SETUP

A prototype of the SOLVENT window was installed in a PASSYS test cell in Porto, Portugal. The test cell used is equipped with the so-called pseudo-adiabatic shell (PAS), which limits the heat loss through the floor, roof and walls to a very low and precisely quantifiable value [3].

Figure 2 shows an external view of the prototype mounted in Summer mode. Table 1 shows the solar optical properties of the clear and absorptive glazings used in the prototype.

Outdoor air temperature and relative humidity, global and diffuse solar radiation, wind speed and direction are measured systematically at the test site as part of the PASSYS measurement protocol. Besides these variables, the test cell and the window prototype were equipped with instrumentation to measure:

- Glazing temperature at each glazing surface.
- Air temperature in the open air channel at different heights.
- Velocity of the air at the centre of the air gap.
- Long wavelength radiation arriving from the outdoor environment to the façade where the window was installed.
- Air temperature at various points inside the test cell.
- Outdoor global and diffuse illuminance on the horizontal plane.
- Illuminance levels at different points in the interior of the test cell.

Figure 2. Prototype of the SOLVENT window mounted on the PASSYS test cell in Summer mode.

The window was tested in Summer mode and in Winter mode, with open air gaps of 2 and 4 cm. Each configuration was monitored for at least one week, each one including at least two days with clear sky.

The heating and cooling system was programmed to keep the internal temperature between 21.0 and 23.5 ºC. In practice, it was found that, during the monitoring period, only cooling was used, and the test room temperature was generally within the cooling control band, at 23.0± 0.5 ºC.

Table 1: Optical and solar properties of the glazings used in the prototype.

	Clear (1 pane)	Double clear (assembly)	Absorptive
Width (mm)	4	4 + 6 (air) +4	5
Luminous Transmissivity (%)	90	81	47
Luminous Reflectivity (%)	8	14	5
Solar Transmissivity (%)	83	70	50
Solar Reflectivity (%)	8	13	6
Solar Absorptivity (%)	9	7	44
Solar factor (EN410)	0.85	0.75	0.61

3. MODEL DEVELOPMENT AND CALIBRATION

3.1 Modelling approach

Most windows are easily handled by thermal and energy building simulation programs. In the case of the SOLVENT window, however, it is necessary to account for the effect of the air flow in the open air gap. Since in most simulation programs the effect of air flow is not accounted, the traditional approach of window integration in building simulation models becomes inadequate. Furthermore, the air flow in the open air gap is driven by buoyancy, which requires the simulation of the combined effect of heat and mass flow.

Potentially, this can be achieved by two methods: (a) CFD simulation or (b) coupled air flow network and energy balance simulation. The first alternative probably has the potential for obtaining more accurate results. However, its implementation depends on many calibration parameters often not available from experimental monitoring. Even more important, the CFD approach requires such computational power that with common computing resources it is impracticable to run whole building simulations for long periods, such as a full year. The approach of coupled air flow network and energy balance, on the other hand, has the potential to simulate long periods and it is easier to calibrate with data currently available from experimental measurements. This kind of approach has been successfully used in the simulation of photovoltaic façades elements and double-skin façades with an opaque wall [4, 5].

3.2 ESP-r base model

This study was based on a simulation model of the test cell, which was developed applying the air flow network approach, as well as the geometry and properties of the materials that make up the test cell and the SOLVENT window. The model was implemented in whole building thermal and energy simulation software ESP-r [6, 7]. As a starting point, the model incorporated only options available in the existing standard ESP-r version.

As an educated guess from previous studies involving buoyancy-induced flow, the open air channel was initially divided into four different thermal zones. Each thermal zone is associated with an air flow network node. The network nodes are linked to their neighbours by components such as air flow ducts and openings. Figure 3 shows a representation of the air flow network obtained for Winter mode. Figure 4 shows a geometric view of the ESP-r model of the test cell with the SOLVENT window mounted.

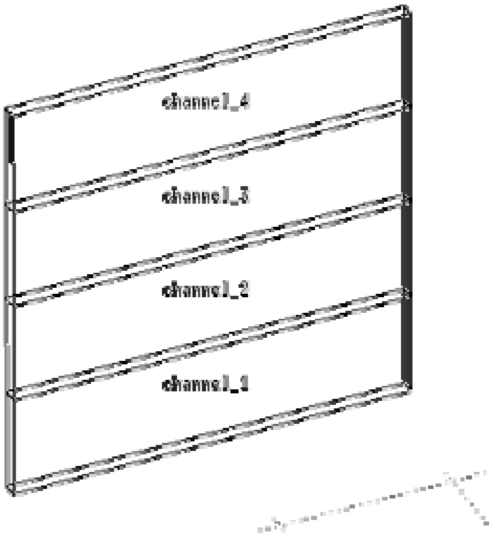

Figure 3. Air flow network in Winter mode.

Heat dissipation of the fan inside the test room was considered as an instantaneous heat gain. The heating and cooling set-points were modelled in the same way as in the real control.

Pressure loss coefficients at the channel entry and at the channel exit were set to the theoretical values for a sudden contraction and for a sudden expansion, 0.5 and 1.0 respectively [8].

The pseudo-adiabatic envelope was initially modelled as a construction formed, from indoors to outdoors, by a layer of aluminium (2 mm) followed by a layer of plywood (12 mm) and a layer of Polystyrene (10 cm). Because the heating foils operate in such a way that the temperature at the back of this panel closely follows the temperature at the inside surface of the test cell, the model initially treated the back of the panel as an adiabatic boundary. It was later found, when comparing with measurements, that this way of modelling the wall causes an overestimation of the thermal inertia of the test cell [9]. In fact, the dynamic response of the experimental results is better replicated by the simulation model if the adiabatic boundary condition in placed right at the back of the aluminium wall. In practice, this means that the opaque envelope of the cell is modelled as a layer of 2 mm of aluminium with no heat flux at the back side. The exception was the South wall, which had no pseudo-adiabatic shell. It was made of (from inside to outside) a 12 mm layer of plywood, followed by 4 layers of expanded polystyrene with a thickness of 50 mm each and a 12 mm panel of white melamine plywood. The wood frame holding the SOLVENT window was also explicitly modelled.

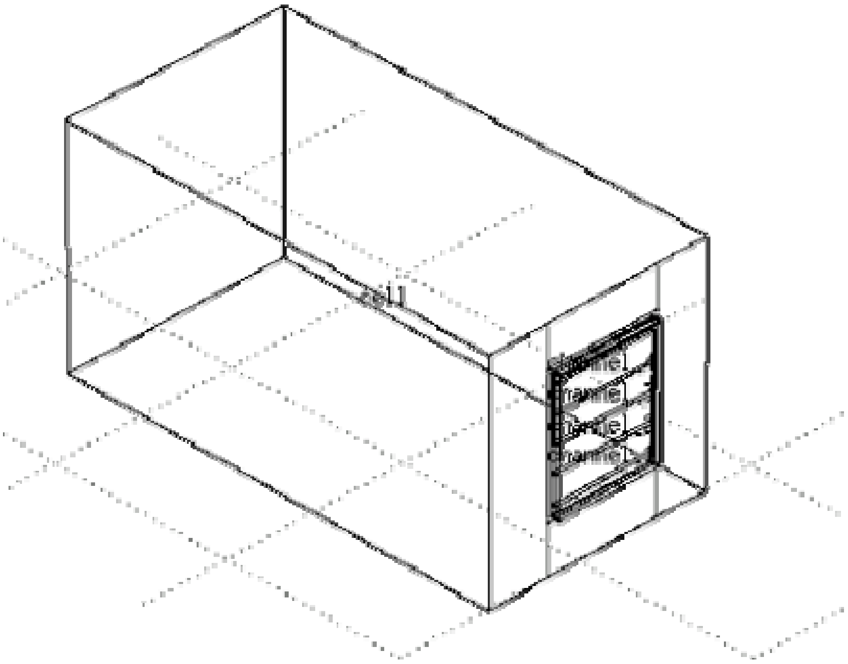

Figure 4. Geometry of the base case model.

Because the window is placed at the centre of a thick wall, there is some shading effect that was taken into account in the simulation model. The angular optical properties of the glazings were obtained from LBLN software Window 5.2 [10].

Meteorological data measured at the test site was used to build a climate file for use in the calibration simulations. The convection correlation for the external surfaces was set as the “MoWitt” correlation [11], which is more appropriate for low rise buildings, as is the case of the test cell. The ground reflectance (albedo) was set to 0.2 and the view factors to ground, surrounding buildings and sky were those typical of a rural site (0.45, 0.10 and 0.45 respectively).

All simulations were run at 1-min time-steps to ensure that the temperature control in the simulation acts as in the real case.

Figure 5 shows the cooling energy as measured and simulated with the base case as described in section 1.3, for the week 2-8 April 2003 (Winter mode, 4 cm air channel). The total cooling energy needed in the period to control the temperature inside the test cell near the setpoint was 24.195 kWh measured and 22.830 kWh simulated, a difference of 5.6 %. The agreement seems satisfactory when the uncertainties always associated with experimental measurements and with the simplifications of the simulation models are taken in account.

When comparing more system specific variables, the quality of the agreement between the simulation and the experimental data is however not as good as for the energy demand values. Figure 6 shows the results for the air velocity in the air channel, making clear that the simulation results are considerably lower than the measured air velocities. This difficulty in predicting the correct air flow can be important if the simulation is being used to optimise the window properties or to study the comfort conditions near the window, for instance.

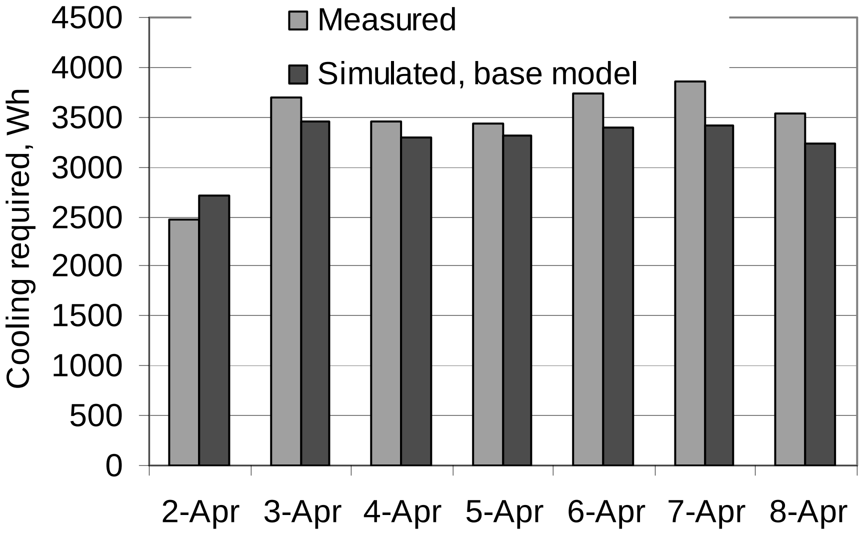

Figure 5. Cooling energy required by the test cell as measured and as simulated with the base case model.

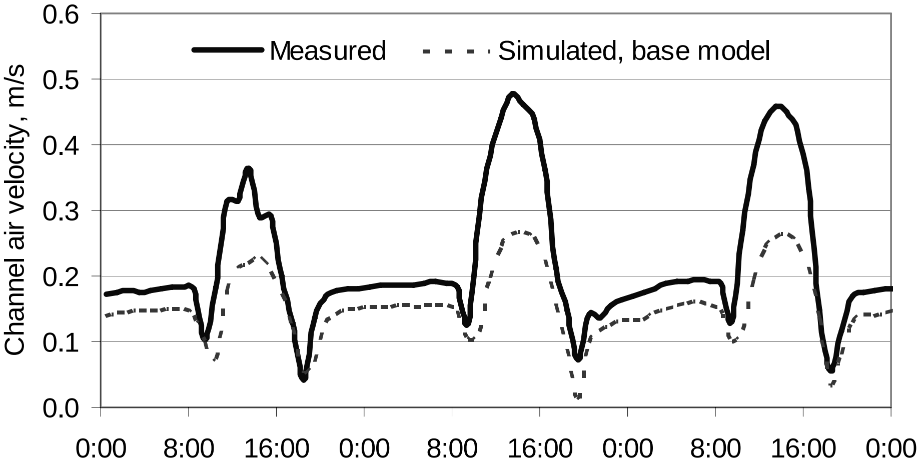

Figure 6. Air velocity in the open air channel as measured and as simulated with the base case model.

A comprehensive set of parametric studies regarding the number of nodes / zone divisions in the open air gap, channel convection coefficient and pressure loss coefficients at the channel entry and exit were performed [9]. The main conclusion was that none of the studied combinations of parameters provided a precise calculation of glazings temperatures and air velocity in the air gap, although the global energy balance for a period of several days could be estimated with an error always between 5% and 10%.

In addition to the difficulties in calculating system-specific variables, it may also be considered that dividing each window into 4 thermal zones can be very time consuming for large projects and greatly increases the complexity of the simulation model.

In order to try to overcome some of the difficulties of the base-case model, it was decided to: (i) perform a more detailed study on the nature and quantification of the heat convection at the open air channel; (ii) develop a specific model for the calculation of the air flow at the open air channel; (iii) integrate the developments of (i) and (ii) in the simulation software.

3.3 New correlation for channel heat convection

Starting from the force balance to the air in the open gap, and from the typical evolution of air temperature along the longitudinal axis in the internal flow in the channel, the following implicit equation for the mean air channel velocity was derived [12]:

$$U = \left\{ \frac{g\left[\rho U S c_p \left(e^{-\frac{2Hh}{\rho U S c_P}} - 1 \right) + 2Hh \right]}{h\left(1 + f\frac{H}{2S} + k_{in} + k_{out}\right)} \frac{\left(T_S - T_{in}\right)}{T_{in}} \right\}^{\frac{1}{2}} \qquad (1)$$

where

- g is the gravitational acceleration constant (m/s^2)
- ρ is the mean air density (kg/m^3)
- U is the mean air velocity at the channel exit (m/s)
- S is the channel pane to pane width (m)
- c_p is the mean specific heat of the channel air (J/kg.K)
- H is the air channel height (m)
- h is the average heat convection coefficient at the channel walls
- T_S is the average temperature of the channel walls (K)
- T_{in} is the temperature of the air entering the channel (K)
- f is the friction coefficient at the channel walls, k_{in} is the local pressure loss coefficient at the channel entry (-)
- k_{out} is the local pressure loss coefficient at the channel exit (-).

Although it can be easily solved in a few iterations, eq.1 still needs to be calibrated in terms of the friction coefficient f, the local loss pressure loss coefficients k_{in} and k_{out}, and the heat convection coefficient h. It was suggested that f is treated according to equation 2 [12]:

$$\begin{cases} f = \dfrac{91.4}{\mathrm{Re}_D} \Leftarrow \mathrm{Re}_D \le 2300 \\ f = \dfrac{0.316}{\mathrm{Re}_D^{0.25}} \cdot \dfrac{91.4}{64} \Leftarrow 2300 < \mathrm{Re}_D \le 10^5 \end{cases} \qquad (2)$$

The local pressure loss coefficients k_{in} and k_{out} were maintained at the standard for a sudden contraction and for a sudden expansion, 0.5 and 1.0, respectively.

Concerning the treatment of heat convection, the comparison of results with experimental values indicated that the measured air velocity is between the values predicted applying the correlations for natural convection at a single plate vertical and for natural convection with free-developed flow (figure 7). The measurement approaches the prediction with single plate convection for low Rayleigh numbers and the prediction with fully developed flow convection for higher Rayleigh numbers.

The Bar-Cohen correlation for natural convection in open vertical air channels [13], along with a proposed correlation specific for the Solvent window [14] were also considered. However, the results showed that none was able to satisfactorily match the experimental results (figure 8).

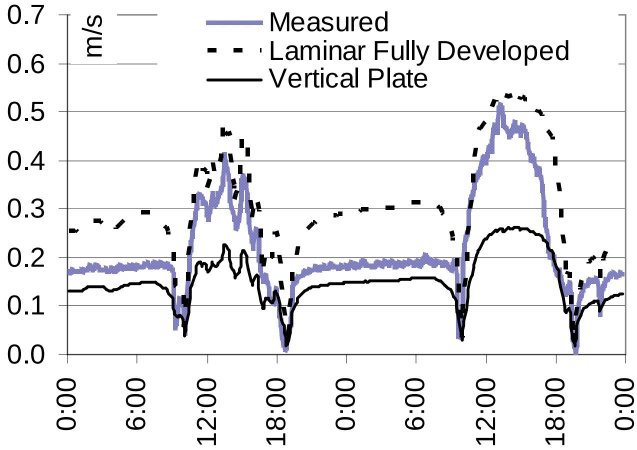

Figure 7. Evolution of air velocity (absolute value) in the channel as measured and as simulated with the two limiting cases for channel convection heat transfer.

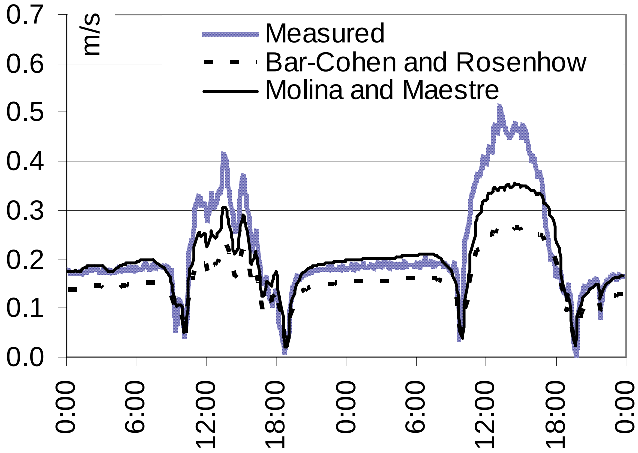

Figure 8. Evolution of air velocity in the channel as measured and as simulated with the two existing correlations for the channel convection.

In an attempt to overcome these difficulties, a new heat convection correlation for the natural convection at the channel walls was suggested [12], combining the limiting cases of single plate and of fully developed convection:

$$Nu_S = e^{-\frac{Ra_S}{C}} Nu_{sp} + \left(1 - e^{-\frac{Ra_S}{C}}\right) Nu_{fd} \qquad (3)$$

where

- Ra_S is the Rayleigh number based on the channel pane to pane width S
- C is a blending constant to be determined experimentally for each aspect ratio S/H
- Nu_{sp} is the Nusselt number for single plate convection
- Nu_{fd} is the Nusselt number for fully developed flow.

For the single plate case, the Churchill and Chu correlation was adopted [15], while for fully developed flow an equation presented in Bejan [16] was selected . This results in equations 4 and 5, where Pr is the Prandtl number.

$$Nu_{sp} = \left\{ 0.825 + 0.387 Ra_H^{1/6} \left[1 + \left(\frac{0.492}{\mathrm{Pr}} \right)^{9/16} \right]^{-8/27} \right\}^2 \cdot \frac{S}{H} \qquad (4)$$

$$Nu_{fd} = \frac{Ra_S}{24} \frac{S}{H} \quad (5)$$

After a brief trial and error procedure, the blending constant C in eq. 3 was set at 4×10^5, for the 4 cm channel. The result is shown in figure 9, which shows a good agreement between the measured and the calculated air velocity.

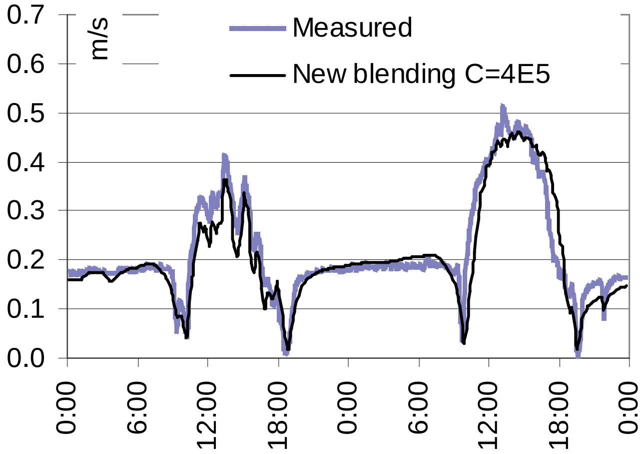

Figure 9. Evolution of air velocity in the channel as measured and as simulated with the new correlation using a blending constant C=4E5.

In Summer mode operation, the openings of the air channel are linked to the outdoor air. Experimental results have shown that, for wind speeds above 1 m/s, the air flow inside the channel is dominated by the wind rather than by the temperature of the glazings that are the walls of the channel (figure 10). Modelling the influence of the wind in the channel flow is a complex fluid dynamics problem that is beyond the scope of this study. However, for purposes of estimating the energy demand of spaces with the SOLVENT window, the experimental results provide an approximated correlation that can be used with good confidence. In particular, the results presented in figure 10 allow a linear correlation between the channel air velocity and the wind speed according to eq. 6, applicable for wind speeds above 1 m/s. For wind speeds lower than 1 m/s, the channel air velocity remains as given by eq. 1.

$$U = 0.1307 \cdot W_S \quad (6)$$

where W_S is the environmental wind speed.

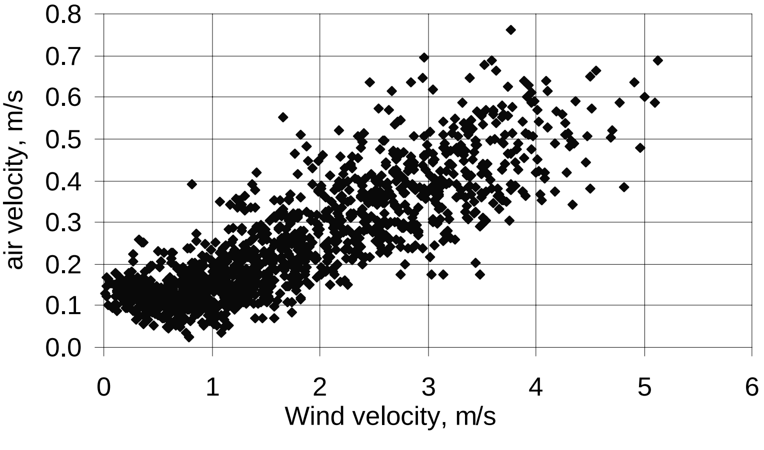

Figure 10. Correlation between channel air velocity and wind velocity for the summer mode configuration with an air gap of 4 cm.

3.4 ESP-r improved model

The fluid dynamics and convective heat transfer models for the air flow in the open air channel, developed and presented in the previous section, were included into the ESP-r code. Two new components were added to the library of flow components, which compute the air flow through the open air gap. One component represents operation in Winter mode, according to eq.1. The other component represents operation in Summer mode, according to eq. 5 if the wind speed is higher than 1 m/s and to eq.1 if it is lower.

The new correlation for heat convection at the air gap (eq. 3) was also included into ESP-r optional treatment of convection at internal surfaces.

A first immediate advantage of the new modelling approach is the fact that there is no need to divide the air channel in several different zones, thus considerably alleviating the modelling effort (figure 11). Furthermore, as expected, there is also a considerable improvement in the accuracy of the results. Figure 12 shows the measured and calculated daily energy demand. With the improved model, the difference in the energy demand falls from 5.6 % in the base case to only 1.3 %. Even more important, system specific variables as the channel air velocity are now better predicted and with good temporal distribution (figure 13).

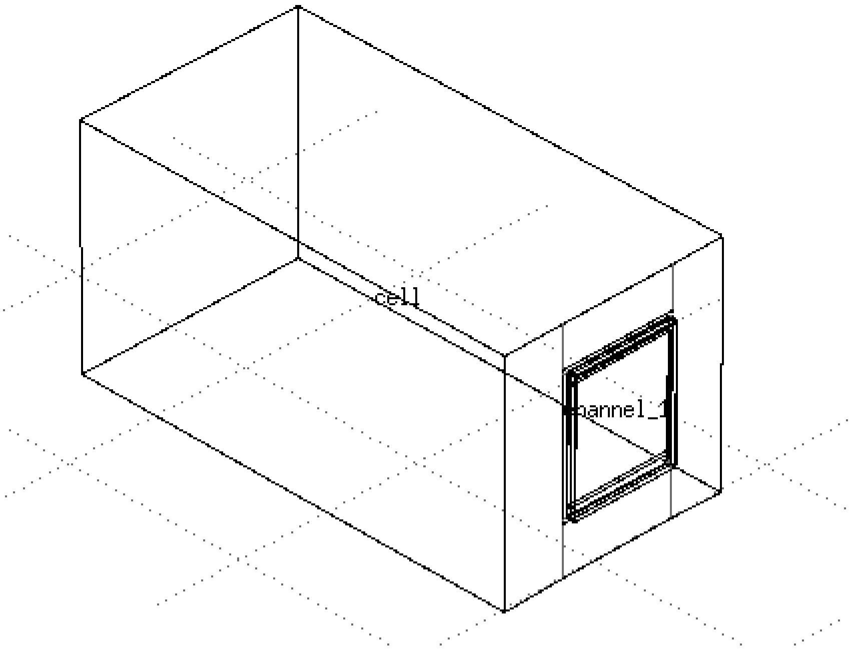

Figure 11. Geometric model of the test cell and associated air flow network with the new SOLVENT flow component.

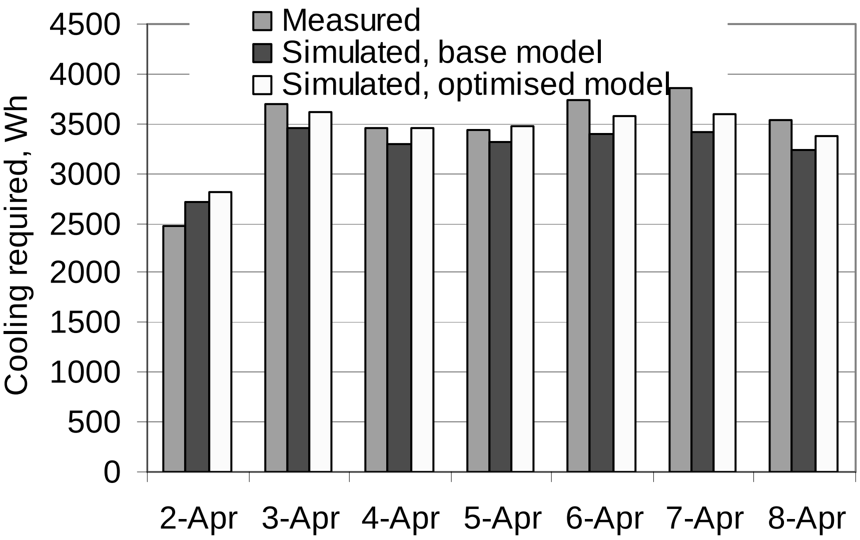

Figure 12. Daily cooling energy required by the test cell as measured and as simulated with the base case model and with the optimised model.

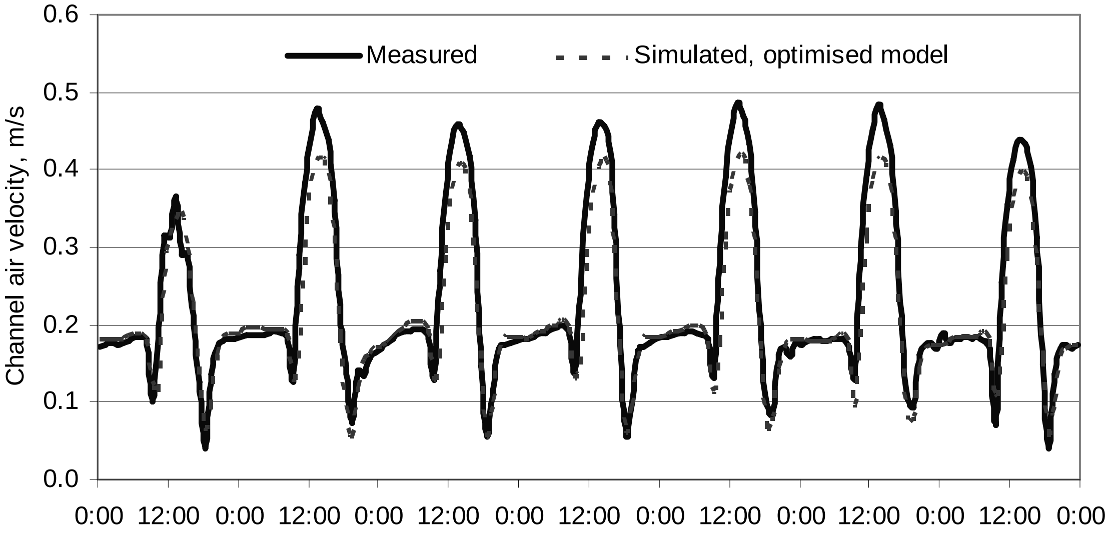

Figure 13. Velocity in the air channel as measured and as simulated with the optimised model.

3.5 Radiance calibration

An important component of the evaluation and optimization of the SOLVENT window is the evaluation of its impact upon daylighting and visual comfort. An especially powerful tool in this area is the software Radiance [17], which was selected for evaluating illumination levels, under several sky conditions, and visual comfort parameters. Although the potential accuracy of Radiance is enormous, in practice its use requires selecting a considerable number of modelling parameters. These parameters affect both the quality of the results obtained as well as the computing time – simulations related with daylighting can be especially demanding [18, 19]. The choice of the simulation parameters by the software user may have huge impact upon the results. It was therefore decided to build a Radiance model of the test cell to use as training case and to select simulation parameters which provide accurate results while requiring a simulation time compatible with common computation resources (i.e., that may run in common PC's).

Two calibration cases were run, one for overcast sky and another for sunny sky.
Figure 14a shows a photographic view of the interior of the test cell, and figure 14b the equivalent view as rendered by Radiance. After an iterative procedure, the main Radiance parameters were identified. Figure 15a displays the illumination levels at the points where the luxmeters were placed, for the overcast sky condition. Figure 15b shows the equivalent data for the sunny sky condition. The agreement between the measured and the calculated values is globally within the measurement uncertainty band. There is therefore an increased confidence in the use of Radiance for carrying out daylighting and visual comfort studies.

Figure 14a. Interior of the test cell (photo).

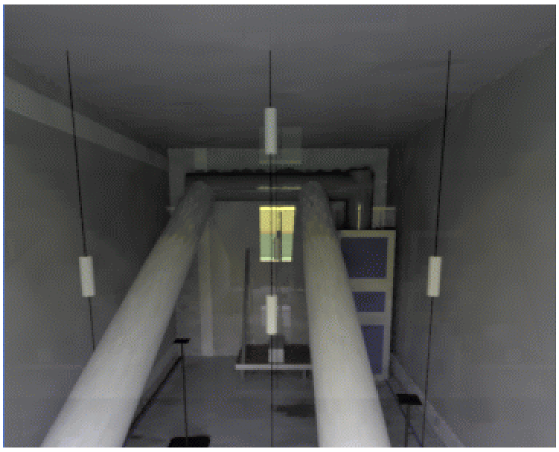

Figure 14b. Radiance rendered image of the interior of the test cell.

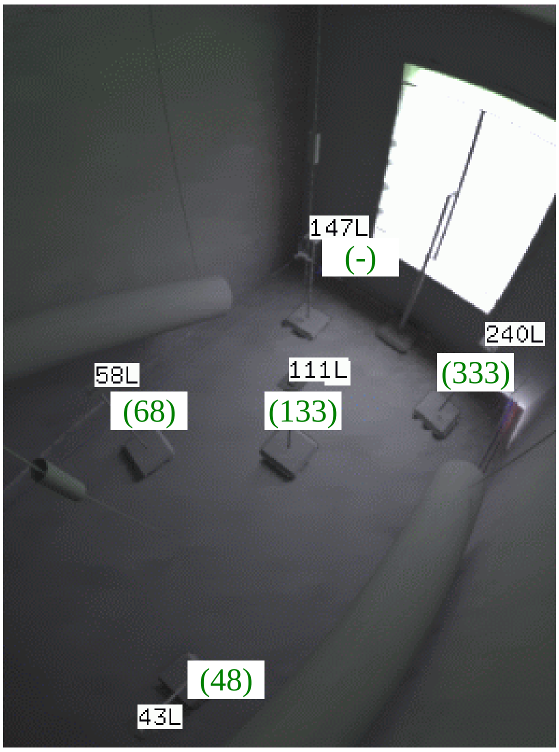

Figure 15a. Simulated illuminance levels under overcast sky conditions and measured values on 5th October at 12:00 (measured values between brackets).

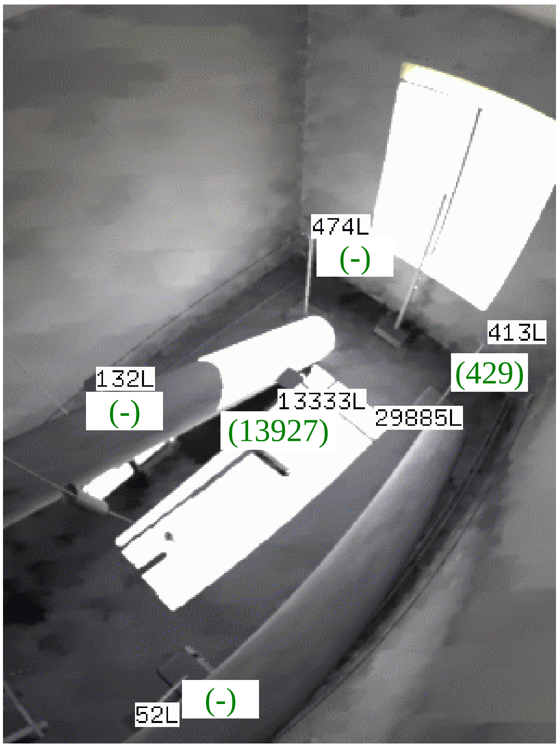

Figure 15b. Simulated illuminance levels under clear sunny sky conditions and measured values on 11th November at 12:00 (measured values between brackets).

4. APPLICATION TO REAL BUILDINGS

The ESP-r model of the SOLVENT window, developed and calibrated with the help of the data acquired at the test cell, was used to study its energetic impact when installed in real buildings.

As an example, consider an office building with a South oriented façade (figure 16a) located in the Faculty of Engineering in Porto, Portugal. Due to the aesthetic criteria of the architect, the building does not have either fixed or movable external shading in the South façade. In the offices, with this orientation, the occupants feel quite uncomfortable with the effect of solar radiation on their visual environment (figure 16b). In sunny days, the internal blinds are often fully closed and electric lighting is turned on.

Figure 16a. Office building (external view).

Figure 16b. Office building (internal view).

The virtual effect of installing SOLVENT windows in two zones on the South-façade of this building was studied with a ESP-r model prepared for this particular case. Besides having a direct impact upon the energy demand for heating and cooling, the SOLVENT window may also affect the use of the internal blinds and electric lighting. As the SOLVENT window has lower transmissivity than double clear glazing, this might result in a higher consumption for electric lighting in low luminance days. Conversely, in sunny days, it may result in less use of the internal blinds and, thus, in lower consumption for electric lighting.

The control strategy adopted in the simulation assumes that the users roll down the blinds when the direct solar radiation impinging on the external façade is higher than a certain set-point, and that electric lighting is activated proportionally to the deficit of daylighting to a given illumination set-point (figure 17). However, the interaction of building occupants with the shading and lighting systems is not a deterministic issue, and there are no standard criteria and set-points for the activation of blinds or for the control of electric lighting [20, 21]. For this particular study, the following values were adopted: i) blinds are closed if the direct solar radiation passing through the window is higher than 150 W/m^2; (ii) Electric lights are dimmed proportionally to the difference between 300 lux and the illumination provided by daylighting alone. Other relevant information regarding building fabric and operation is summarized in table 2.

Table 2. Main envelope and operation characteristics of the reference room.

Room area (m^2)	30.10
External Walls U-Value (W/m^2.K)	0.69
Roof U-Value (W/m^2.K)	0.55
Mean (fresh) air change rate (ach^{-1})	1.0
Internal gains	- 3 PC's 100% time + 2 PC's 50% time + 1 printer in standby - Eight 36 W lamps from 9 to 18 h - 5 people. Simultaneity factor 70%
Heating set-point	20 ºC
Cooling set-point	24 ºC

A specific change to the ESP-r code was made to allow the control of blinds placed within glazings in façades that, in the simulation model, are linked to other zones of the building and not directly to outdoors.

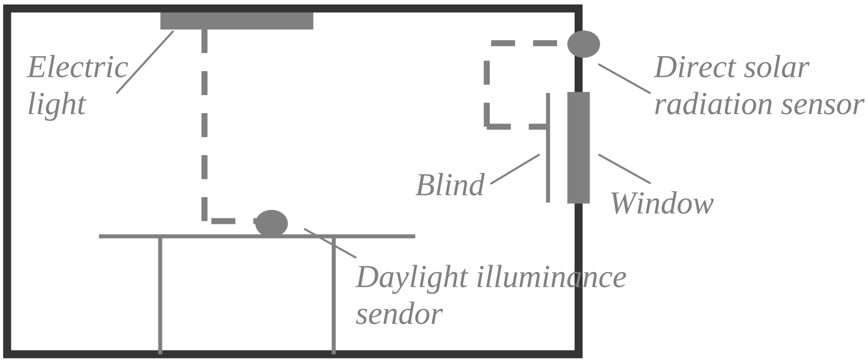

Figure 17. Simulation strategy for controlling electric lighting and internal blinds.

Several simulations were run considering different types of glazing systems. Figure 18 compares the energy demand of a reference room in terms of local energy (figure 18a) and in terms of primary energy (assuming that cooling is provided by a heat pump with an average COP of 3, heating is provided by a boiler with efficiency of 80%, and that the efficiency in the conversion from fossil fuel to electricity is 40%). For this office and the Porto climate, the results of the SOLVENT window are better than those of a double clear glazing and than those of a double-glazed, non-ventilated, solar control window, with a special advantage in terms of requirements for cooling. The difference with the SOLVENT window installed, in terms of primary energy is 27% fewer needs than the double clear glazing window and 8% less needs than the solar control window.

Besides having a better energy performance, the SOLVENT window also provides better visual comfort in sunny days. Figure 19 shows the Daylight Glare Index, as calculated with Radiance, for a point in the reference room. A reduction of about 2 points in the DGI glare scale is observed.

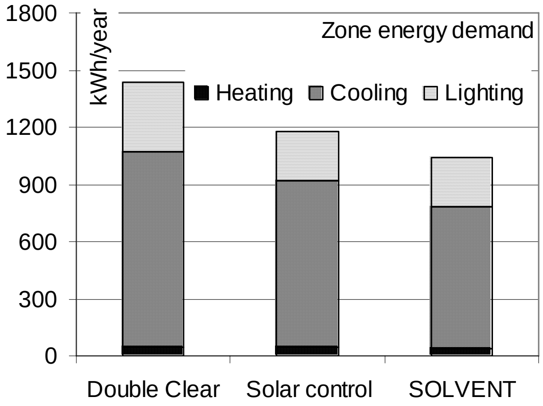

Figure 18a. Local energy demand of the reference room.

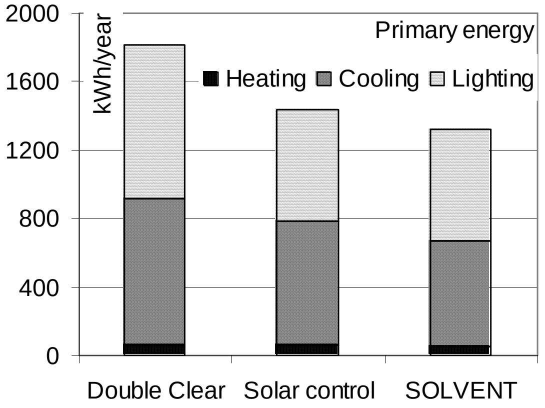

Figure 18b. Energy consumption of the reference room, expressed in primary energy (equivalent to natural gas).

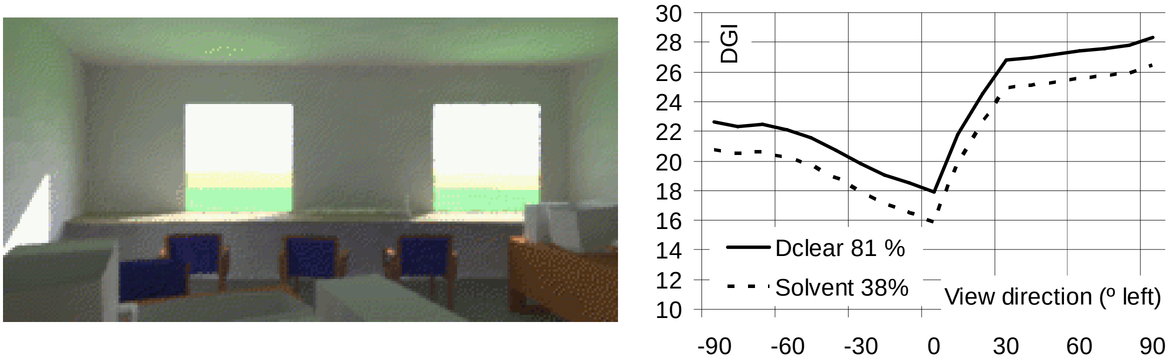

Figure 19. Daylight Glare Index for a reference view point in the room, as function of the view direction and of the glazing used.

6. CONCLUSIONS

Integrating innovative building components into thermal and energetic simulation of buildings can often be difficult. Even when the component can be somehow modelled in the simulation software, it is important to have experimental data that may help to calibrate those models or, if necessary, to develop improved models for the simulation of the component and its integration in the global simulation of the building.

In this study, a prototype of the SOLVENT window installed in the PASSYS test cell was used to achieve these objectives. The experimental data allowed the evaluation of a base-case simulation model, which was found to be reasonable but improvable. More specific models for air flow and heat convection were developed and validated, then integrated in the code of the simulation software. Even when there is no need to intervene at the level of the source code, experimental data can be used for training and adjusting the way in which simulation programs are used (as was the case of Radiance in this study).

After the development of the component models was concluded, using the PASSYS test cell as a small-scale building, its application to realistic buildings can be performed with increased confidence in the results. In the present case, it was possible to estimate that the application of the SOLVENT window to an office in Porto, when compared with a double clear glazing window, would allow a reduction of 27% in the primary energy consumption for heating, cooling and lighting. The improvement becomes 8% when comparing with a double glazed solar control window.

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