

MODELLING A REVERSIBLE VENTILATED WINDOW FOR SIMULATION WITHIN ESP-R - THE SOLVENT CASE

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ABSTRACT

Whole building simulation may play a key role in the optimization and assessment of the market potential of new building components. In the SOLVENT Project, ESP-r was used for such purposes, in the case applied to a new reversible ventilated window.

The innovative character of the window required the development of a specific simulation approach within ESP-r, in order to account for buoyancy in the air channel. A multi-zone approach with an air flow network was developed, and several variations studied. Parametric studies assessed the effect of the number of zones into which the window is divided, heat transfer correlations for the air gap and local loss coefficients for the air flow network.

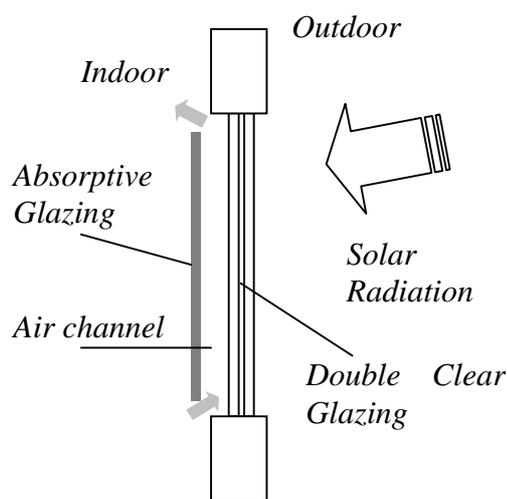
An experimental measurement campaign performed in the PASSYS test cell in Porto allowed calibration and verification of the simulation model.

INTRODUCTION

The use of clear windows in buildings is a common way to provide daylight and solar energy to rooms in buildings. In many buildings, especially those located in places with frequent sunny sky, visual comfort problems arise, e.g., glare. Users are often prompted to use internal or external solar protection devices, which in turn reduce energy gains in the heating season and may prompt them to use electrical lighting.

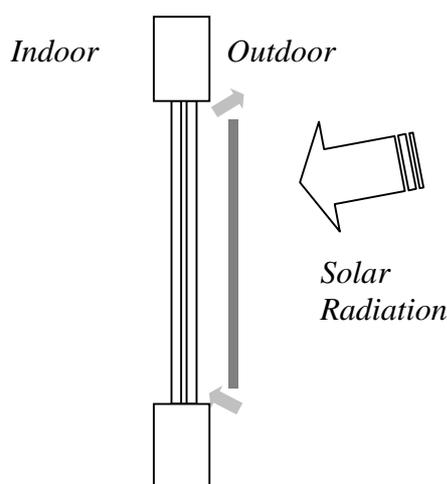
In an attempt to solve the visual comfort problems without compromising the energy performance, Etzion and Erell (2000) proposed an innovative glazing system, here called the “SOLVENT window”.

The SOLVENT window is shown in figure 1. It is essentially a ventilated window with a conventional double clear glazing on one side and a dark absorptive glazing on the other side of the channel. The window frame allows a rotation in such a way that the absorptive glazing faces indoors in the winter mode and outdoors in the summer mode (Erell et al, 2002).



Winter mode

Figure 1 a): SOLVENT window in winter mode



Summer mode

Figure 1 b): SOLVENT window in summer mode

The physical principle of the system is the interception of solar radiant energy by the absorptive glazing and its conversion into convective heat and long wave radiation. As the absorptive glazing heats up, it will create natural convection air flows in the

air channel and along its free face. A correct quantification of the energy flows is thus essential for evaluation of the SOLVENT window energy performance when integrated in real(istic) buildings.

The development of this glazing system was the aim of an EU project named SOLVENT. One of the project goals was to study the energy impact of the window on several types of buildings in various climates. The thermal simulation software ESP-r (ESRU, 2000; Clarke, 2001) was selected for this purpose.

Modelling the SOLVENT window within ESP-r in a conventional way could not account for the flow in the air channel and the heat convected by this means. A special procedure was thus needed, capable of accounting for the buoyancy in the air channel and of describing the induced air flow.

MODELLING APPROACH

To account for the combined effect of heat and mass flow in building simulation, two alternatives can be considered:

- i) CFD simulation
- ii) Air flow network coupled with energy balance.

The first alternative probably has the potential to achieve more accurate results. However, several reasons render it difficult to implement in practice. As one of the goals is to obtain results for long periods (frequently a complete year), the dynamic simulation of the air flow in the channel, if at all possible, would require computational resources much beyond the scope of the study. Along with this difficulty, the experimental setup necessary for calibrating and validating a CFD model is usually complex.

The second alternative provides a method compatible with simulation of long periods, and it is easier to calibrate and integrate with other heat fluxes such as solar radiation absorption in the glazings, long wavelength exchanges between the glazings, etc. This kind of approach has been used in the simulation of PV façade elements (Clarke et al., 1997) and double-skin façades with one opaque wall (Hensen et al., 2002).

The use of this technique requires that the air channel be divided into two or more thermal zones, linked to each other and to external nodes by components. Figure 2 represents an ESP-r model of the SOLVENT window constructed according to this approach.

While the physical description of the system and the inclusion of the angular-dependent optical properties of the absorptive glazing and of the double-clear

glazing are straightforward, there are a number of questions that may require some research:

- i) The number of zones into which the window must be divided.
- ii) The heat transfer coefficient values or correlations that shall be used in the air channel surfaces.
- iii) The localized pressure loss coefficients for the inlet and outlet of the channel.

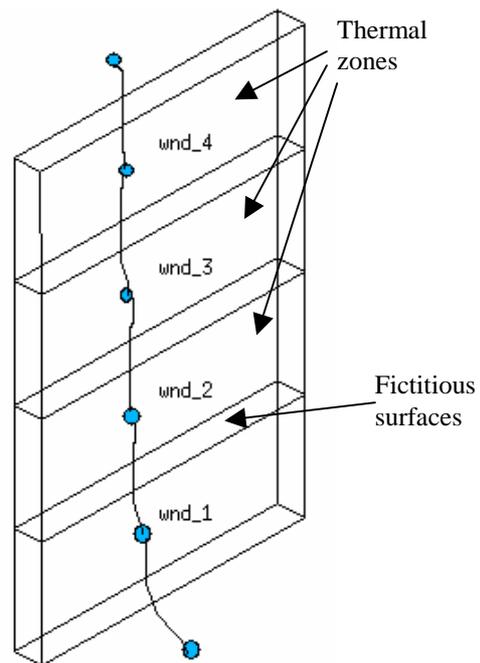


Figure 2: SOLVENT window air network modeling

The assessment of the adequacy of the possible parameters and the calibration the simulation model were obtained by considering a window mounted in a PASSYS test cell in Porto (Vandaele et al, 1994). An ESP-r model of the test cell integrating the SOLVENT window was developed for comparison of simulation results with measurements. Figure 3 shows a representation of the model geometry.

The base case was built before specific measured data became available, so it may represent the approach of a modeller who has no prior data.

The window was divided into four thermal zones, vertically interconnected. The division into several thermal zones was intended to account for the pressure variation and buoyancy effects, but the number of zones itself (4) was arbitrary.

The default heat transfer coefficients computed by ESP-r were used for all surfaces.

Regarding localized pressure drop coefficients, they were computed from standard fluid mechanics relations (Munson et al, 1998), using $K_{in}=0.5$ for the

inlet and $K_{out}=1$ for the outlet. Curve effects were neglected because the elbows were coincident with the inlet/outlet and because they were very smooth.

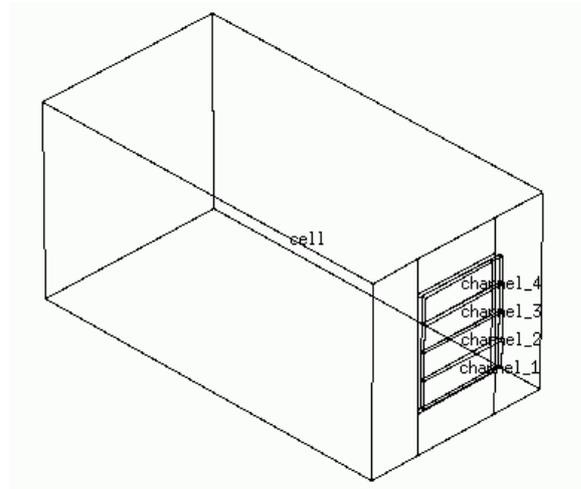


Figure 3: ESP-r model of the PASSYS test cell in Porto with the SOLVENT window integrated.

EXPERIMENTAL SETUP

The experimental setup comprised a SOLVENT window installed in the PASSYS test cell located in Porto and instrumentation to monitor its thermal and daylighting behaviour. Figure 4 shows a view of the SOLVENT window (in summer mode) installed in the test cell and some associated instrumentation (Leal et al, 2002-1).

The main monitored quantities were, along with outdoor climatic variables, the absorptive glazing temperature, the clear glazing temperature at both panes, the air temperature at different heights in the air channel and the air velocity in the centre of the channel. Figure 5 shows a scheme of the window and measuring instrumentation. Some interesting difficulties associated with temperature measurement under incidence of strong solar radiation were identified but are out of the scope of this paper and left for discussion elsewhere (Leal et al, 2002-2).

NUMBER OF ZONES

It has been reported (e.g. Clarke et al., 1997; Hensen et al., 2002) that the division of a window into several zones linked by an air flow network has the potential to account for buoyancy and natural convection effects. No rule has however been given which allows the determination of the number of divisions needed.



Figure 4: Prototype of the SOLVENT window (in summer mode) installed at the PASSYS test cell.

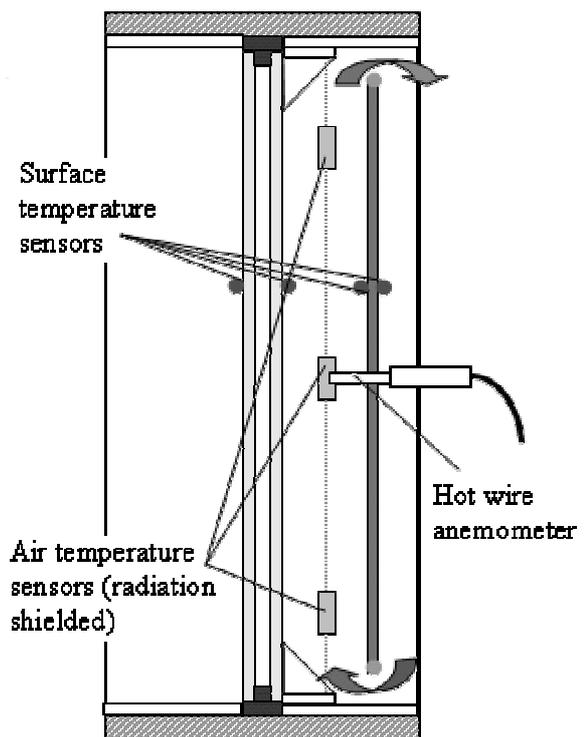


Figure 5: Location of measurement sensors.

This section presents a parametric study of the number of zones into which the window air channel should be divided and the comparison of results with measurements in the test cell. Alternatives considered were models with window comprising 1, 2, 4 or 8 zones. Convection calculations were left in ESP-r default mode and the local loss coefficients were also kept at $K=0.5$ for the inlet and $K=1.0$ for the outlet of

the air channel. Simulations were performed for the Winter mode (i.e., with channel open to indoors) in order to minimise the effect of wind.

Results show hourly averages of system temperatures and air velocity for a period of three days starting at 0:00 h of November 8th 2001, and daily cooling needs for the period 29 October-13 November. An error analysis is also presented in table 1, showing absolute mean deviation between simulation and measurements as computed by:

$$AMD = \frac{\sum |X_{simul,i} - X_{meas,i}|}{n} \quad (\text{eq. 1})$$

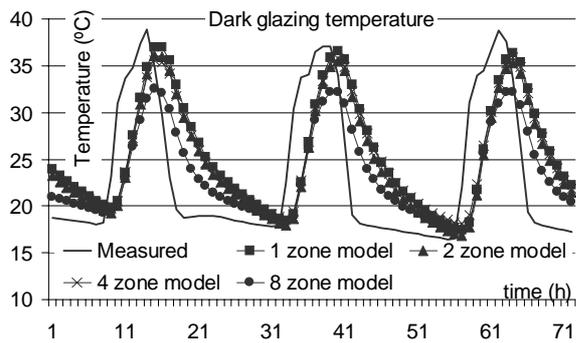


Figure 6: Absorptive glazing temperature as measured or simulated with several alternatives.

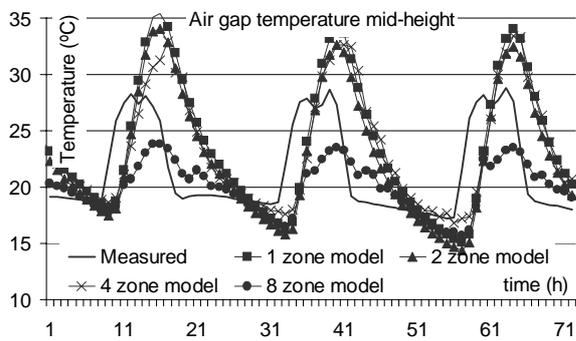


Figure 7: Air temperature at channel mid-height as measured or simulated with several alternatives.

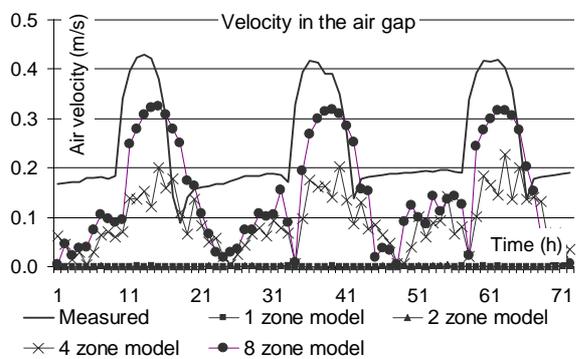


Figure 8: Air velocity at channel mid-height as measured or simulated with several alternatives.

It can be noted that there is a substantial dependence of the simulation results upon the number of zones into which the window is divided. The simulated values of the temperature of the tinted glazing using models with 1, 2 and 4 zones nearly overlap. Values are similar to measured temperatures, but thermal inertia seems to be clearly overestimated in the simulations. The 8-zone model, however, leads to lower temperature predictions, with peak differences around 5°C.

In the prediction of air gap temperature mid-height, models with 1, 2 or 4 zones lead again to similar results, but simulated values in this case are somewhat higher than measured temperature. The 8-zone model, on the other hand, underpredicts the air gap temperature.

The issue of air gap velocity is particularly sensitive to the number of divisions. 1 or 2-zone models were not able to simulate the air flow. The 4-zone model predicts some flow, while predictions derived from the 8-zone model are clearly closer to the measured velocity. It must be noted that ESP-r presents as output the volumetric or mass air flow, and not the air velocity. Calculated air velocity represents an average value for the cross-section, assuming uniform profile.

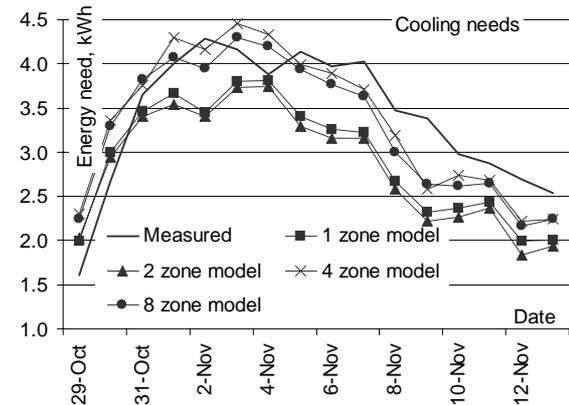


Figure 9: Cooling needs as measured and as simulated with several alternatives.

Table 1: Absolute mean deviation between simulated and measured values.

Number of zones in model	1	2	4	8
Absorpt. glazing temperature (°C)	6.0	5.5	5.7	4.6
Air gap temp. mid-height (°C)	4.6	4.1	4.1	2.8
Velocity in the air gap (m/s)	0.24	0.24	0.15	0.11
Cooling needs (kWh/day)	0.50	0.57	0.30	0.32

Finally, with respect to the cooling needs of the test cell, the 4-zone and 8-zone models performed noticeably better than the 1-zone or 2-zone models, but with little difference between them. This issue

was considered decisive in this study, since the aim was to simulate the impact of the window upon building energy consumption.

HEAT TRANSFER COEFFICIENT

Since the window is being treated as a set of thermal zones, the heat transfer coefficients computed by ESP-r for the inner surfaces of the air channel are the same as for room internal surfaces. These are usually computed by Alamdari-Hammond correlations. A more specific correlation for laminar channel flow with isothermal walls can be found in the literature (Bar-Cohen and Rosenhow, 1984):

$$Nu_S = \left[576 \left(Ra_S \frac{S}{H} \right)^{-2} + 2.87 \left(Ra_S \frac{S}{H} \right)^{-0.5} \right]^{-0.5} \quad (\text{eq. 2})$$

The resultant heat transfer coefficient, depending on the aspect ratio S/H and on the temperature difference between the surfaces and the air at the inlet is plotted in figure 10. For a window 1 m high, with an air gap of 4.5 cm and a ΔT slightly below 20°C a value of $h=3.0 \text{ W/m}^2\cdot\text{K}$ is representative.

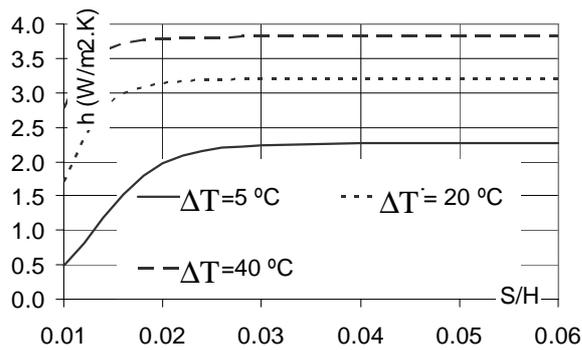


Figure 10 Heat transfer coefficient in the air gap according to equation 2.

In practice, however, the air flow in the air gap is not always laminar, the glass panes are not isothermal and may have different temperatures, etc. Based on experimental data from the SOLVENT window, Molina and Maestre (2002) suggested the following correlation for a 4.5 cm air gap channel:

$$h = 3.00 \Delta T^{1/3} \quad (\text{eq. 3})$$

This correlation leads to substantially higher heat transfer coefficients. For instance, with a difference of 20 °C between the average temperature of the glazings and the temperature of the entering air, the predicted heat transfer coefficient is $8.1 \text{ W/m}^2\cdot\text{K}$.

Changing the convection coefficients within ESP-r is possible by imposing fixed h values for pre-defined periods or by selecting a pre-defined correlation that will be active whenever the HVAC system is active in the zone (Beausoleil-Morrison, 2001).

It is known from boundary-layer theory that heat transfer coefficients are higher at the beginning of the surface and then decrease (with the possibility of increasing again if there is a transition to turbulent flow at a certain point). This study developed in the frame of length-average heat transfer coefficients, and thus a uniform value was assumed for the entire area of the surface modelled.

This study considered three different alternatives:

- i) Default correlations (Alamdari-Hammond);
- ii) An imposed value of $h=3.0 \text{ W/m}^2\cdot\text{K}$ from 8:00 to 20:00 (approx. during daytime).
- iii) An imposed value of $h=8.0 \text{ W/m}^2\cdot\text{K}$ from 8:00 to 20:00 (approx. during daytime).

A fourth alternative, corresponding to the dynamic use of the correlation in eq.3, i.e., with heat transfer coefficients being calculated at each time-step, has also been attempted. However, the default mechanism implemented in ESP-r that allows imposing a correlation considers the temperature difference *between the surface and the air in the zone*. Imposing a correlation considering the temperature difference *between the glazing and the air entering the channel*, as in eq. 3., would require non-trivial changes to the source code and therefore this alternative was discarded due to time availability constraints.

The number of window zones was kept at 4 and the sum of local pressure loss coefficients at $K=1.5$.

Results of measurements and simulations are presented in figures 11 to 14. These results show that the method of calculating the heat transfer coefficient had little effect on the accuracy of the predictions for the temperature of the tinted glazing and for the velocity in the air gap. All alternatives also gave similar predictions for the air gap temperature, except the alternative with $h=8 \text{ W/m}^2\cdot\text{K}$, which yielded results closer to measured values (though still with substantial deviations), thus confirming the validity of analysis reported by Molina and Maestre, eq. 3.

Regarding the prediction of the cooling load, fundamental to the assessment of the window energy performance, none of the alternatives was clearly better than the others. Errors in the predicted cooling needs for the entire period 29th October-13th November were less than 1.0% for all alternatives. However, there were non-negligible differences among predictions at a daily level.

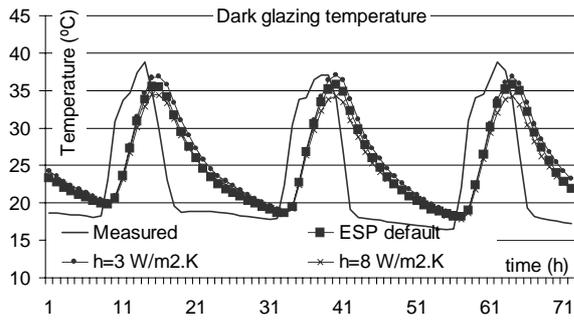


Figure 11: Tinted glazing temperature as measured and as simulated with several alternatives.

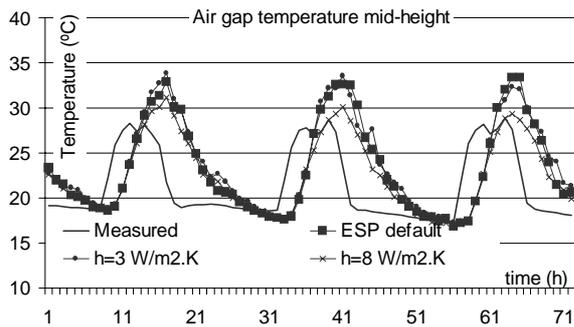


Figure 12: Air temperature at channel mid-height

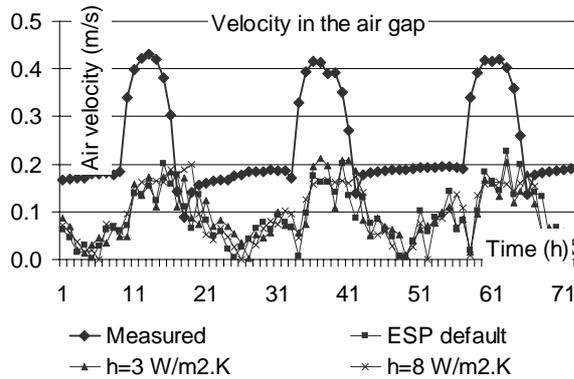


Figure 13: Air velocity at channel mid-height

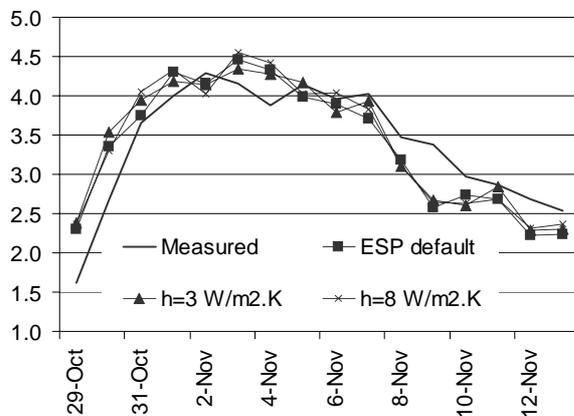


Figure 14: Cooling needs.

Table 2: Absolute mean deviation between simulated and measured values.

	ESP default	h=3 W/m ² .K	h=8 W/m ² .K
Absorpt. glazing temperature (°C)	5.7	6.3	5.7
Air gap temp. mid-height (°C)	4.1	4.4	3.4
Velocity in the air gap (m/s)	0.15	0.15	0.15
Cooling needs (kWh/day)	0.34	0.33	0.37

LOCALIZED LOSS COEFFICIENT

The construction of an air-flow network requires the input of local pressure drop coefficients. The pressure loss at the considered obstruction is given by:

$$\Delta P = \frac{1}{2} K \rho V^2 \quad (\text{eq. 4})$$

The standard value of K is 0.5 for a sudden contraction (such as the channel inlet) and 1.0 for a sudden expansion (such as the channel outlet). These are however only recommended values, since the exact values depend strongly on the geometry of the streamlines in each particular case.

For this study, three alternatives were considered:

- i) K=1.5, based on the standard approach;
- ii) K=0.2, representing a scenario of low streamline dispersion;
- iii) K=2.0, representing a scenario of higher streamline dispersion, also coincident with the value that Sandberg et al. (2002) reported as leading to good agreement with experimental results.

The number of window zones was kept at 4 and heat transfer coefficients kept in the default mode.

Results for the different alternatives and measurements are shown in figures 15 to 18.

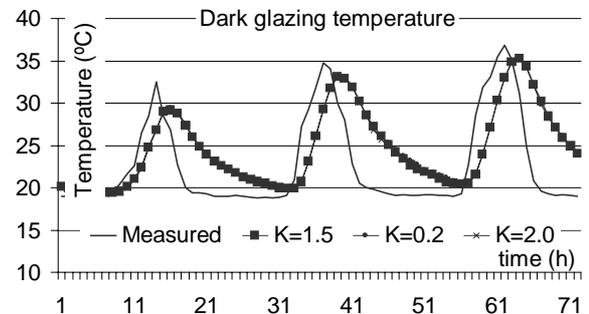


Figure 15: Dark glazing temperature as measured and as simulated with several local loss coefficient alternatives.

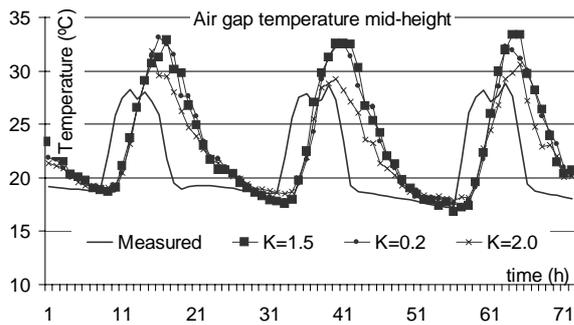


Figure 16: Air temperature at channel mid-height as measured and as simulated with several local loss coefficient alternatives.

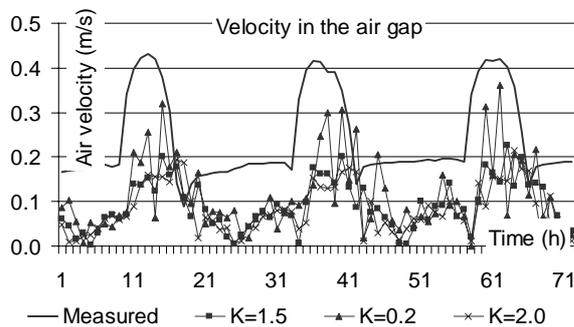


Figure 17: Air velocity at channel mid-height as measured and as simulated.

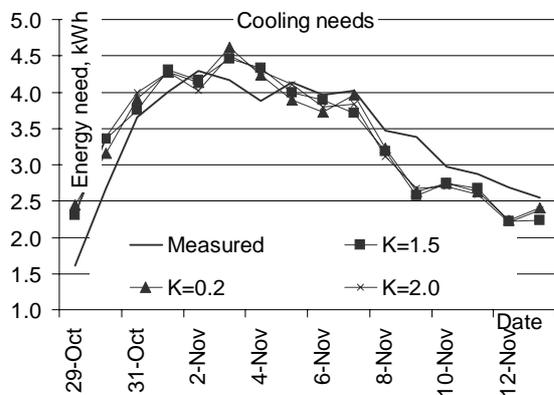


Figure 18: Cooling needs as measured and as simulated.

Table 3: Absolute mean deviation between simulated and measured values.

	K=1.5	K=0.2	K=2.0
Absorpt. glazing temperature (°C)	5.7	5.7	5.7
Air gap temp. mid-height (°C)	4.1	4.1	3.2
Velocity in the air gap (m/s)	0.15	0.13	0.16
Cooling needs (kWh/day)	0.34	0.34	0.36

Results show that the influence of the sum of the local loss coefficients in the range analysed is low, except in the following aspects:

- The option K=2.0 led to better results in terms of air gap temperature.

- The option K=0.2 led to better results in terms of air velocity in the channel.

CONCLUSIONS

The present study compared the effects of several modelling approaches for a ventilated window, all based on an air flow network. The study focussed on the influence of the following parameters: the number of zones into which the channel is divided; the method for calculating heat transfer coefficients; the values of local pressure loss coefficients.

It was found that the sensitivity of the results to the studied parameters follows the same order:

- The most important parameter is the number of zones in which the window is divided; this is especially important for the assessment of air flow rates in the air channel.
- The second parameter is the heat transfer coefficient.
- The less important parameter is the local loss coefficient.

Generally the results of this study show that the accuracy of the results is satisfactory in terms of heating and cooling loads for long periods such as days or months. There is, however, a perceptible overestimation of thermal inertia in ESP-r simulation, which may have an important impact if there is a dynamic HVAC control of the zone. There seems to be some room for improvement in terms of prediction of particular system variables such as glazing temperatures or air flow rates, which may be important in certain cases.

As the main objective of these simulations in the context of the SOLVENT project was to predict long-term heating and cooling loads, the optimum method for simulation of the window in realistic buildings, was as follows:

- Each window was divided into 4 zones.
- A heat transfer coefficient of $h=8.0 \text{ W/m}^2\cdot\text{K}$ was imposed during daytime.
- The sum of the local loss coefficients was set to K=0.2.

The 8-zone model performed better in terms of air flow in the channel but not so well in terms of

system temperatures. It is also difficult to implement in the simulation of buildings with a large number of windows.

Finally, it should be noted that, by treating the window as a set of thermal zones, it is not possible to use ESP-r facilities to evaluate daylighting in the interior zone to which the window is adjacent. Further development of ESP-r to overcome this limitation may be desirable.

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REFERENCES

- Etzion Y. and Erell E. "Controlling the transmission of radiant energy through windows: A novel ventilated reversible glazing system", *Building & Environment*, 35(5):433-444, 2000.
- Erell et al, "SOLVENT: Development of a reversible solar-screen glazing system", proceedings of the Energy Efficient & Healthy buildings in Sustainable Cities - EPIC 2002 AIVC conference, Lyon, France, 23rd-26th October 2002.
- ESRU: The ESP-r system for Building Energy Simulations: User Guide Version 9 Series, ESRU manual U00/01, University of Strathclyde, Glasgow UK, 2000.
- Clarke, J.A.: "Energy Simulation in Building Design-2nd Edition", Butterworth-Heinemann, 2001.
- Clarke J A, Johnstone C, Kelly N and Strachan P A: "The Simulation of Photovoltaic-Integrated Building Façades". Proceedings of the Building Simulation 1997 conference, Prague Czech Republic, 1997.
- Hensen JLM, Bartak M, and Drkal F., "Modelling and simulation of double-skin facade systems," in *ASHRAE Transactions*, vol. 108:2, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, USA. 2002
- Vandaele, L. and Wouters, P.: "The PASSYS services: Summary report", European Commission publication EUR 15113 EN, 1994.
- Munson B R, Young D F, Okiishi, T H, "Fundamentals of Fluid Mechanics", John Wiley and Sons, 1998.
- Leal V, Borges M and Maldonado E, "Final Report on the experimental testing of the Solvent

window in Porto", Appendix nr. 6 of the SOLVENT Final Report., 2002.

- Leal V, Borges M and Maldonado E, "On the measurement of temperatures ", Appendix nr. 7 of the SOLVENT Final Report., 2002.
- Bar-Cohen and Rohsenow, "Thermally optimum spacing of vertical natural convection cooled, parallel plates", *J. Heat Transfer*, 106, 116., 1984.
- Molina J L and Maestre I R, "Energy exchanges in the ventilated cavity of the SOLVENT glazing system: Modelling and experimental validation", Appendix of the SOLVENT Final Report., 2002.
- Beausoleil-Morrison, I: "Flow responsive modelling of internal surface convection", Proceedings of the Seventh international IPBSA Conference, Rio de Janeiro, 2001.
- Sandberg et. al., "Final Aerodynamic Report", Appendix of the SOLVENT Final Report, 2002.

NOMENCLATURE

- Nu_S – Nusselt number based on the channel with S.
- Ra_S - Raleigh number based on the channel with S.
- S – Channel width (m).
- H – Channel height (m).
- h – Convective heat transfer coefficient (W/m².K).
- ΔT - Temperature difference between the average glazing temperature (considering the two sides of the air channel) and the air entering the air channel (K).
- ΔP - Local pressure drop at a certain point of the air flow path (Pa).
- K – Local pressure loss coefficient.
- ρ - Air density (kg/m³).
- V – Average air velocity at the location of the obstruction to the air flow (m/s).
- $X_{simul,i}$ - Simulated value of quantity X at hour i.
- $X_{meas,i}$ - Measured value of quantity X at hour i.
- n – number of hours used for comparison between measurements and simulation.