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"SOLVENT": development of a reversible solar-screen glazing system

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Abstract

Preliminary experiments with a novel glazing system developed at the Desert Architecture and Urban Planning Unit of Ben-Gurion University of the Negev in Israel indicated that it may provide improved visual and thermal performance in buildings with large glazed areas located in sunny regions, regardless of orientation. In winter, it reduces glare, local over-heating and damage to furnishings caused by exposure to direct solar radiation, with only a small reduction in solar space heating. In summer, it reduces the penetration of unwanted radiation without obstructing the view through the window, to an extent that may render external shading devices unnecessary. The SOLVENT project was contracted to complete the development of the glazing system, which is based on the concept of converting short-wave solar radiation to convective heat and long wave radiation. The glazing system was modeled and evaluated experimentally; a suitable frame was developed for it; and a design tool required for its application was developed. The current paper reports on physical modeling and experimental evaluation of the glazing system.

Keywords: Visual comfort; Daylighting; Reversible window; Advanced glazing

1. Background

In sunny climates (hot or cold), windows may have several drawbacks.

- Direct exposure to solar radiation often results in visual discomfort due to glare, thermal discomfort due to high radiant load and deterioration and fading of furnishings.
- Large glazed areas are useful in winter, but may cause over-heating in summer.

Conventional architectural design deals with solar radiation in an essentially 'binary' approach: it is either desirable, in which case it should be allowed to penetrate to the building interior; or it is undesirable, in which case it should be intercepted by the glazing system and shading devices.

This binary approach is acceptable in many locations.

In cold or overcast climates, solar radiation is nearly always desirable, and illumination levels are rarely excessive. Building energy performance is best served by glazings with a high solar transmittance combined with a low thermal transmittance. This is achieved by applying low e-coatings on clear glass or on thin polyester films in a multi-layer glazing system. The center-of-glass heat transfer coefficient of typical glazing systems is now in the range of 1–1.5 $W/m^2 K$, so it is possible to have a net seasonal gain from glazed surfaces even in very cold climates [1]. Conductivities of lower than 0.5 $W/m^2 K$ have been reported for aerogel glazing [2], but these 50 mm thick panels are translucent, providing diffuse daylighting, and have no seasonal variability.

In warm and sunny climates, the penetration of solar energy to building interiors is generally not desirable from thermal considerations. The problem is thus one of providing effective natural lighting without imposing a penalty in terms of unwanted heat, and of allowing a view outdoors. The approach to solving these seemingly conflicting requirements has been to develop spectrally selective glazings. While most

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tinted glazings absorb solar radiation in all parts of the spectrum, spectrally selective coatings suitable for daylighting in warm climates have a high visible transmittance but relatively low solar transmittance, since they absorb a substantial proportion of the near infrared radiation emitted by the sun. The appropriateness of a glazing for warm climates may be measured by an index called the glazing luminous efficacy, K_c, which is defined as the normal visible transmittance (T_{vis}) of a glass divided by its shading coefficient (SC) [3]:

$$K_c = \frac{T_{vis}}{SC} \quad (1)$$

In many mid-latitude locations, however, such as parts of the Mediterranean, winters are sufficiently cold so that solar energy for space heating is desirable, yet summer conditions mandate extensive protection from solar radiation. The traditional approach in such countries has been to install shading systems, either fixed or operable. Seasonal adaptation in fixed shading is the result of differences in the relative position of the sun, but cannot respond to short-term variation in temperature and solar radiation, and suffers from the inherent lag between minimum temperatures and minimum insolation. Operable shading allows user control over solar gain, but does not distinguish between visible light and the rest of the solar spectrum.

Much current research is being devoted to the development of electro-chromic glazing, whose optical characteristics may vary in response to the application of an electric current [4]. Laboratory samples have demonstrated high transmittance in the bleached state—up to about 80%, coupled with a high attenuation in the colored state, with a solar transmission as low as about 25% [5]. Electro-chromic glazing, once it becomes available commercially, may thus provide good visual comfort in changing environmental conditions. However, it too does not resolve the problem of conflicting requirements from a building-energy standpoint and daylighting design.

Seasonal response has also been explored through the use of angle-selective glazings, which transmit varying proportions of solar radiation as a function of the incidence angle. The angle-selective response, designed to correspond to solar altitude at the relevant location, may be achieved by means of external coatings on the glass [6], or by means of minute prisms etched onto the glass surface [7]. However, to gain maximum benefit from such glazings, the angular selectivity must be specifically tailored for each location and each orientation of the window opening. These glazings are still experimental; they, too, are translucent; and they are not spectrally selective.

Integrated shading devices are sometimes found in the form of Venetian blinds placed between the glass sheets in a double glazed unit, or between the frames of a double window [8,9]. If the cavity between the interior and exterior panes of glass comprising these windows is vented, airflow may be established in this space, allowing air to be either returned to the building interior via an air handling system, or exhausted to the exterior. The so-called 'airflow windows' were reported to have several advantages over conventional insulating glass, including better control of condensation on the glass and higher mean radiant temperatures (in winter). However, solar control was provided by Venetian blinds—sacrificing energy efficiency for daylight control. A variant of the airflow window is the use of an insulation screen open at the top. The effects of various configurations of a γ thermosiphon were investigated, and good thermal insulation and solar protection were reported [10]. However, in all such windows, the air path is fixed throughout the year, and no adaptation to the differing seasonal requirements is possible.

All of these solutions provide only a partial response to the problems outlined above. They offer a compromise between what are often two contradictory requirements: in order to provide visual comfort and prevent high radiant temperatures near the window, they block solar energy that may be required to heat the building, sacrificing energy performance. They also block the view outdoors, to a certain extent. The novelty of the approach explored in the following paper lies in the attempt to maximize the benefits of solar radiation from a building energy point of view, yet to provide acceptable visual comfort and to reduce the undesirable side effects of direct-gain systems.

A glazing system seeking to control radiant transfer while preserving the benefits of solar heating by direct gain was proposed by Etzion and Erell [11]. The benefits of the glazing system are realized mainly through the conversion of short wave (solar) radiation to convective heat and long wave radiation (Fig. 1). The system requires an innovative reversible frame, incorporating two glazing assemblies: a clear glazing to provide a weatherproof seal, and an absorptive glazing to provide solar control. The two glazing assemblies and the ventilated channel between them rotate together through 180° to enable the transformation from winter mode to summer mode.

- In summer, the glazing system reduces the penetration of solar radiation to the building interior, while allowing

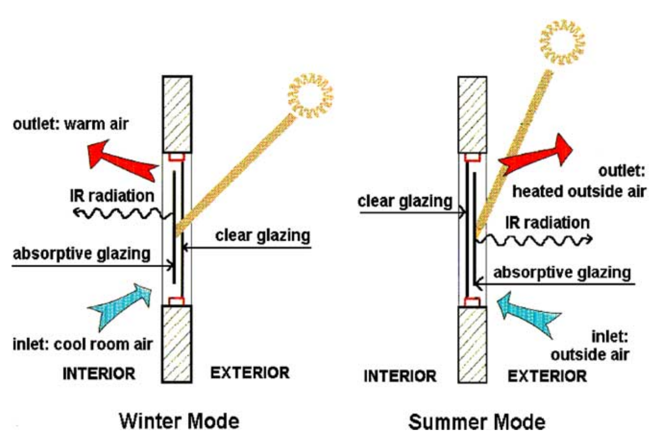

Fig. 1. Concept of the SOLVENT glazing system.

an unobstructed view. It lowers the cooling load (saving energy), improves visual comfort and decreases thermal discomfort near the glazing to an extent that may render shading devices unnecessary.

- In winter, the glazing system allows solar space heating with only a small loss of efficiency compared to direct gain systems, but increases visual comfort in the heated space; it reduces local overheating caused by exposure to direct solar radiation; and it diminishes damage to furnishings in the interior space due to solar radiation.

The objectives of the SOLVENT project were to model the aerodynamic and thermal behavior of the proposed glazing system with respect to various combinations of environmental conditions, glazing types and window geometry, and to optimize its performance; to design a fully reversible frame; to test the performance of the system under different climatic conditions; and to provide practical design guidelines for architects and lighting consultants. For convenience, the glazing system developed within this project will henceforth be referred to as the 'SOLVENT window'.

This paper deals mostly with the aerodynamic design and with results of the experimental monitoring. The thermodynamic relationships describing the behavior of the glazing system will be introduced briefly: the full analytical models developed within the project are the subjects of separate papers.

2. Overview of thermal and aerodynamic models

The thermodynamic model of the glazing system [12] presents the relationship between the optical characteristics of the glazing, the dimensions of the system components and the behavior of the system under varying environmental conditions. It consists of two elements, dealing with the aerodynamic characterization of the system and with thermal exchange with the environment.

The aerodynamic element of the model predicts the average velocity of the air in the gap as a function of the amount of heat it absorbs from the glass. It is coupled to the thermal component in an iterative procedure whereby an initial velocity is used to calculate the integrated temperature difference between the air gap and the surrounding air, allowing the calculation of a buoyancy force and hence a 'real' velocity. The procedure is terminated when the heat balance equations incorporating the convective heat component in the air channel with all other radiative and convective components are within a prescribed tolerance.

Air velocity in the channel is given by the following simplified expression:

$$v = \left[a \frac{g(\Delta T/T)H}{1/2(1 + f(H/2d) + k_{\mathrm{in}} + k_{\mathrm{out}})} \right]^{1/2} \quad (2)$$

where g is acceleration due to gravity, ΔT the temperature rise in the air gap, T the air temperature at the inlet, H and d are the height of the window and the glass-to-glass distance, respectively, f is the Darcy friction coefficient and k_{in} and k_{out} are the inlet and outlet loss factors. a is a factor that describes the distribution of energy input to the system (from solar radiation absorbed in the glass), and is given by:

$$a = \frac{1}{qH} \int_0^H q(z)\, \mathrm{d}z \quad (2a)$$

where q is the heat flux into the air, H the window height and z the vertical coordinate of position.

In terms of the temperature distribution the factor a can be expressed as:

$$a = \frac{1}{\Delta T\, H} \int_0^H (T(z) - T_i)\, \mathrm{d}z \quad (2b)$$

In expression (2), the following two terms have been neglected.

(a) Acceleration due to the change in density of the air between the inlet and outlet.
(b) Change in momentum flux due to a change in the velocity profile between inlet and outlet.

Assuming uniform temperatures in the panes limiting the gap, and uniform (known) film coefficients (in principle, a different value may be calculated for each side) in the gap, the equation obtained for the temperature evolution of the air in the gap is:

$$T(z) = HT_{12} + (T_i - HT_{12}) \exp(-Az) \quad (3)$$

where

$$HT_{12} = \frac{h_1 T_1 + h_2 T_2}{h_1 + h_2} \quad (3a)$$

$$A = \frac{(h_1 + h_2)W}{\dot{m} c_{\mathrm{p}}} = \frac{h_1 + h_2}{\rho c_{\mathrm{p}} v d} \quad (3b)$$

and $T(z)$ is the average air temperature at height z from the inlet; T_i inlet air temperature; T_1, T_2 are average temperatures of the two glass panes forming the channel; h_1, h_2 the convective heat transfer coefficients for both glass surfaces; $\dot{m}$ is air mass flow rate in the gap; c_{p} the heat capacity of air; ρ the air density; v the air velocity; d and H are ventilated gap thickness and height; and W is the width of the channel.

3. Detailed aerodynamic design

One of the main functions of the proposed glazing system is to convert solar energy into convective heat (in addition to long wave radiation). The properties of the ventilated space between the glazing assemblies have a direct effect on the airflow in it, and thus on the proportion of energy absorbed in the glazing which may be removed by convection. Careful aerodynamic design is required to increase this component—to improve mixing of the warm air produced

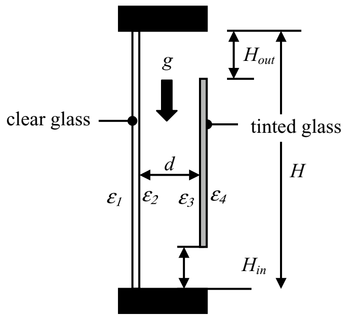

Fig. 2. System parameters for heat transfer and aerodynamic design.

with the interior room air (in the winter mode), and to reduce the effect of warm air in the ventilated channel (in summer).

The study focused on the following:

- The width of the ventilated gap (pane-to-pane distance between the absorptive glazing and the clear glass).
- The minimum height required to set up a thermosiphonic flow, as a function of the incident solar radiation, the absorptivity of the glass and the dry bulb temperatures of the internal air and the surroundings.
- The optimal relationship between the height and the width of the glass, for a glazing unit of given area.
- The design of the inlet and outlet of the ventilated air space.

Fig. 2 is a schematic drawing of the glazing system, illustrating the parameters investigated from the point of view of heat transfer and resistance to air flow.[1]

The initial modeling, CFD analysis and experimental studies on a laboratory mock-up showed that the velocity variations along the air gap are relatively small [13]. The maximum convective heat transfer from the glass to the air in the ventilated channel occurs when the convective surface heat exchange coefficient (h) is greatest and when the temperature difference between the glass and the air is largest. This in turn implies the following:

1. Air flowing through the channel should be in contact with the entire surface area of the glass.
2. Air velocity near the glass should be as high as possible (to increase h).
3. Aerodynamic resistance to the flow should be minimized (to maximize $\dot{m}$, thus reducing ΔT for any given rate of heat exchange).

The detailed aerodynamic analysis [14] resulted in the following recommendations for the design of the SOLVENT window:

- Inlet and outlet: The ratio between height of the opening and the distance between the glass panes, H_{in}/d and H_{out}/d for the inlet and outlet respectively, should not be less than 0.5.
- The edges of the absorptive glass should be provided with a rounded profile.
- For air gaps of up to 5 cm (considered a practical limit for window construction), the aspect ratio of the gap (the ratio between the height of the air gap, H, in relation to the separation distance between the glass panes, d), should be <70. For a given window height H this means that the minimum separation distance is equal to $d = 0.014H$.

[1] For clarity, the clear glass is depicted as a single pane. If the clear glazing consists of two or more panes of glass, the properties of each surface are treated in a similar manner.

3.1. Aerodynamic optimization of inlet and outlet

The effect of the shape of the profiles at the top and bottom of the absorptive glazing on the flow in the air gap between the window panes was investigated for three different cases: (1) glass edge (i.e. no additional profile); (2) circular wood profile; (3) wing-shaped wood profile.

The profiles were attached at the bottom of the absorptive glass while the top of the pane was left without a profile during this test (See Fig. 3. In the figure, the window frame and jambs are omitted for clarity). The absorptive glazing was heated by means of an electrical heating foil. Its exterior surface was insulated with polystyrene insulation, so that the entire heat input was directed into the ventilated channel. The power supplied to the heating foil was kept constant at 200 W/m^2. The air gap was 20 mm, with chamfered sill and head as shown in the figures.

The air velocity in the ventilated gap was estimated by measuring the time for a smoke tray to pass the channel. In order to make smoke visualizations possible, a piece of the jamb was cut out and replaced by a Plexiglas window.

The flow pattern at the entrance was observed for the three different cases. The air velocity in all configurations was about 0.4 m/s—no significant difference could be observed among the three cases with the instrumentation used here. However, the flow patterns show some difference as can be seen from Fig. 4. (The wing-shaped profile gave the same pattern as shown for the circular profile and is not shown.)

Two boundary layers are formed at the inlet, merging together into a single layer about twenty centimeters above it. When the glass edge is sharp (no profile attached), separation occurs at the edge. The wake is clearly visible, and a tendency for re-circulation to occur was observed during the test, although not captured in the photo. The circular profile makes a smooth edge with a radius of 6 mm that is enough to prevent separation of the flow from the glass surface under the circumstances studied here. The exact shape of the profile is probably not critical and may be determined from technical and architectural considerations, as long as the profile has smooth and rounded corners with a radius of not less than 6 mm. The profile must of course not cause any obstruction of the channel.

The modeling study reached several conclusions regarding the properties of the airflow in the channel.

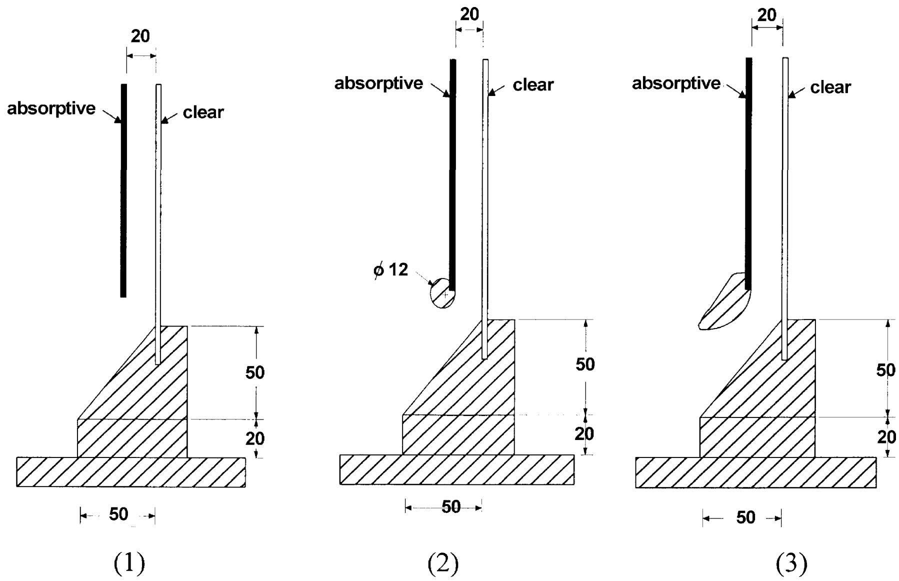

Fig. 3. Aerodynamic configurations of inlet studied. (1) Glass with no additional profile; (2) circular wood profile; (3) wing-shaped wood profile. (All dimensions in mm.)

Fig. 4. Visualisation of flow at inlet with no profile (left) and when the glass edge is provided with circular profile of radius 6 mm (right).

- Given the distance between the glass panes, the temperature difference between the glass and the air, and the velocity of the air, the model predicts that the flow in the channel will be transitional, i.e. both laminar and turbulent.
- Given the operational characteristics of the test windows, and a glass-to-glass separation of up to 5 cm, the boundary layers at each of the two glass faces forming the channel will merge if the height of the window is greater than approximately 1 m.
- Even though the glass surface is aerodynamically smooth, friction may not be neglected for windows with the recommended aspect ratio (i.e. the ratio between height and glass-to-glass distance is <70). Since the flow is predicted to be turbulent in at least part of the channel, the turbulent friction coefficient may be used, i.e. $f = 0.04$.
- On the assumption that the inlet opening has a similar section to the channel, the inlet loss factor was found to equal approximately 0.5 (which is the standard value), or somewhat larger, due to the change in the direction of the flow.
- On the assumption that the outlet is likewise similar in cross-sectional area to the duct, the contraction coefficient tends to unity and the outlet loss coefficient tends to zero. Small losses may nevertheless be measured due to curved flow as the air stream exits the duct.

4. Performance monitoring and model validation

Prototype windows were installed at three test sites to evaluate the performance of the glazing system under different climatic conditions, and to verify and calibrate the thermal and aerodynamic models:

- Cottbus, Germany, representing a cold continental climate (PASLINK cell [15]).

Fig. 5. The SOLVENT window installed in the PASLINK test cell at Cottbus, summer configuration.

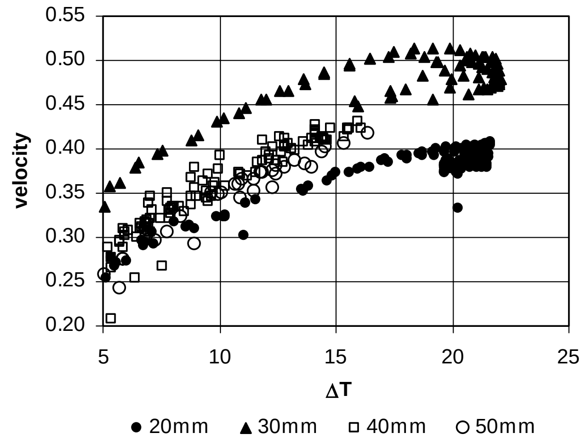

Fig. 6. Relation between ΔT (the temperature difference between outlet and inlet of air gap (°C)), and the flow velocity in the channel (m/s), for four different air gaps. (Sde-Boqer test cell, February, 2002).

- Porto, Portugal, representing a mild maritime climate (PASLINK cell).
- Sde-Boqer, Israel, representing desert climates (a masonry test building with two test rooms [16]).

Monitoring was carried out in each of the sites in winter and summer. Detailed data were collected describing surface temperatures of all glazing components, air velocity and air temperature in the ventilated channel, daylight distribution in an adjacent interior space and environmental conditions. Fig. 5 shows an exterior view of the Cottbus test cell with the SOLVENT window installed. Detailed descriptions of the test cells and experimental procedures are given in [17–19].

4.1. Air speed in the ventilated channel

Air speed in the ventilated channel was measured at one point only, at the middle of the channel (in all axes), using a hot-wire anemometer (Table 1). A correction factor for this reading is necessary since the horizontal profile of the velocity in the channel is not flat: When the glass-to-glass distance is small, friction with the glass has a dominant effect on the flow and a substantial portion of the cross-section may be considered to be in the boundary layer of one of the panes or the other. The velocity profile in the air gap of a window identical to the one used in the field trials was, therefore, measured at the HIG laboratories in Gävle using a high precision laser Doppler anemometer, and a correction factor introduced for the hotwire measurements, as follows.

The relatively large error in measurement of the air velocity in the small pane-to-pane distance is explained by fact that at the lowest separation distance the velocity profile is curved; increasing the separation distance results in a flatter profile, in which case a reading near the middle is more representative.

Fig. 6 shows the relationship between air speed and the thermal driving force, represented by ΔT, the difference in air temperature between the top of the ventilated channel and the mean value for the room, for four different gap widths. The graph presents flow conditions between 10:00 and 17:00 on sunny days, when the thermal flow was stable and fully developed. (Sunny days were defined here as days when there were no clouds, and global radiation received on the surface of the window had a maximum value of 850–900 W/m^2.) The window was monitored in the winter mode, so that environmental wind did not affect the flow in the gap. The normal solar transmissivity of the tinted glass in all cases was 0.27, and apart from the change in gap width, the configuration of the windows was identical.

For each gap width, the general relationship between ΔT and the velocity of the air, derived by regression analysis, has the form $V = A\Delta T^B$, where A and B are constants with values in the ranges of 0.15–0.25 and 0.25–0.40, respectively. For any given value of ΔT, the velocity of the flow was lowest when the air gap was 20 mm wide, due to friction with the glass, and highest when it was 30 mm. Increasing the pane-to-pane distance further, however, resulted in decreasing velocity.

The temporal development of the air velocity in the ventilated channel displayed a characteristic daily pattern (Fig. 7). Once a sufficient temperature difference was established between outlet and inlet of the channel, flow accelerated rapidly, reaching a limit of about 0.4–0.55 m/s, depending on the aerodynamic resistance of the channel in the specific

Table 1
Relative error of the one-point method of measuring air velocity in the ventilated gap

Pane-to-pane distance (cm)	Relative error (%)
2	26
3.5	−1
5	6

Positive values indicate measured values are too high.

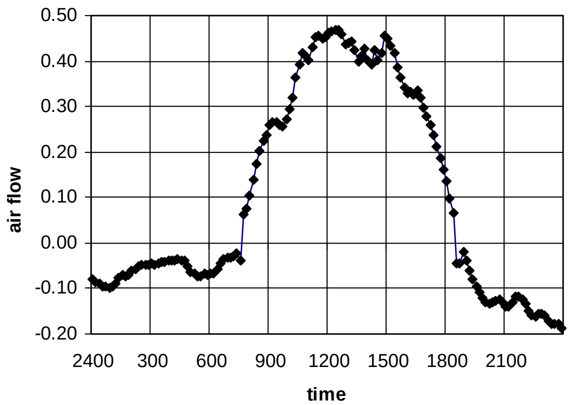

Fig. 7. Temporal development of the air flow in the ventilated channel on a typical sunny day. Sde Boqer, 6 February 2002. Gap width: 30 mm. (Negative values denote downwards flow.)

configuration. At night, when the glass was exposed to strong radiative cooling, a weaker downwards flow of about 0.1–0.2 m/s was observed. (In a separate experiment, a similar downwards flow was also measured at night near a conventional window exposed to the same conditions.)

4.2. Heat transfer coefficient of glass surfaces facing the channel (assuming the same value for both surfaces)

The heat transfer coefficient at each of the glazed surfaces was calculated from the heat balance equation for the appropriate surface, with the measured air temperature, air speed in the ventilated channel and temperatures of the glass surfaces as inputs.

Assuming constant h, the theoretical expression for the air temperature evolution in internal flow is [20]:

$$\frac{T_S - T(x)}{T_S - T_i} = e^{-(Ph/\dot{m}c_p)x} \qquad (4a)$$

where T_S is the (average) glazing temperature (K), $T(x)$ the air temperature at x distance from channel entry (K), T_i the temperature of the air entering the channel (K), P the channel cross section perimeter (m; here $P \cong 2W$, W being the window width), h the average heat transfer coefficient in the air channel (W/m^2 K), $\dot{m}$ the mass flow rate of air (kg/s;) and c_p the air specific heat (J/kg K).

Having measured the glazing surface temperatures and the air temperatures at channel entry (T_{in}) and at three quarters channel height ($x = 3/4H$), the average surface heat transfer coefficient in the air gap may be derived from the following expression:

$$h_{channel} = -\frac{2}{3}\frac{\rho c_p v S}{H} \ln\left(\frac{T_s - T_{3/4}}{T_s - T_{in}}\right), \quad \text{where } T_s \approx \frac{T_1 + T_2}{2} \qquad (4b)$$

and ρ is the density of air (kg/m^3); c_p the heat capacity of air (J/(kg K)); v the velocity of air in the channel (m/s); S the cross sectional area of the channel (m^2); H the channel height (m); T_s the mean temperature of the glass surfaces facing the channel, T_{in} and $T_{3/4}$ are the air temperature at the inlet and three quarter height, respectively, and T_1 and T_2 are the temperatures of the absorptive and clear glazing, respectively (K).

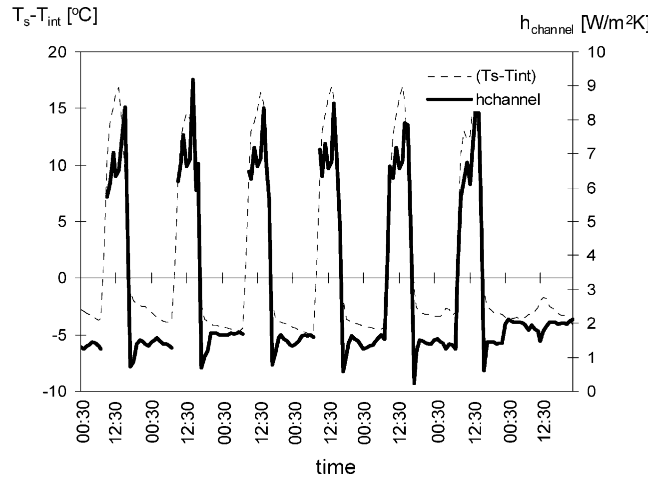

Fig. 8. Evolution of the temperature difference $T_S - T_{int}$ between the glass and interior air and of $h_{channel}$, and of the heat transfer coefficient in the channel surfaces. (Porto test cell, 8–14 November 2001.)

The surface heat transfer coefficient is shown in Figs. 8 and 9 as a function of time and of the temperature difference between the glazed surfaces forming the channel walls (T_s) and the room air (T_{in}), respectively.

4.3. Validation of the model

In the full thermal model [12], the matrix equations can be solved and the temperatures of the system can be calculated if the optical properties and the convective film coefficients of the window elements are known. However, the specific geometry of the SOLVENT system and the thermal conditions likely to occur in it may result in flow conditions that are not dealt with in the standard literature on the

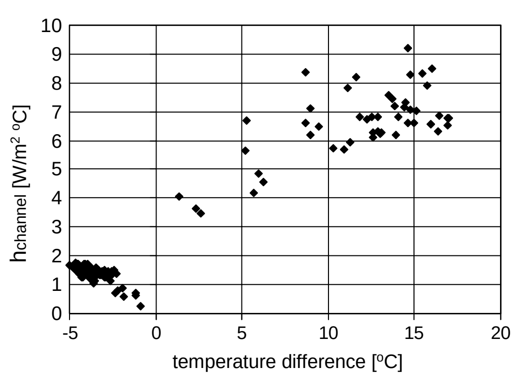

Fig. 9. The heat transfer coefficient at the surface of the glass facing the air channel as a function of temperature difference between the glazing temperature (average of the two glazings) and the indoor air.

subject. Experiments were, therefore, conducted to calibrate a model that could predict the behavior of the SOLVENT prototype in a variety of conditions. This model could then be used in a two-fold way: to compare different designs and to evaluate possible energy impacts on heating and cooling a building fitted with SOLVENT windows.

The film coefficients of all glazed surfaces— exterior, inside the closed air gap and inside the room—were first calculated using standard correlations. Comparison of measured values with model predictions led to the following observations:

(1) The general trends were well described, albeit the errors were not negligible.
(2) The errors were systematically higher in the afternoon than in the morning.
(3) The predicted values for the film coefficient of the exterior glass (which was exposed to forced convection, and dominated by the wind velocity) were too low.
(4) There was some delay between the maximum radiation and the maximum temperature.

Two possible explanations for the discrepancy were proposed: measurement error and insufficiently accurate modeling. Several tests were carried out to determine the accuracy of the measured data [21], especially with respect to measurement of the surface temperature of glass exposed to strong radiant loads and of the air temperature in the ventilated channel. The use of radiation shields was found to be essential. However, since such shields also interfere with convective exchange, temperature readings were found to be excessive by as much as 2 °C in certain conditions. With respect to the model, two components were considered suspect: inaccurate determination of the surface heat exchange coefficients, especially of the glass surfaces facing the ventilated channel; and inadequate characterization of radiant exchange with outdoor surfaces to which the window is exposed.

Modifications were made to the model with the aim of minimizing the deviation between the values of four parameters predicted by the model and those recorded in the experiments: T_{sa} the outlet temperature of the air; T_0 the temperature of the outer glass, T_1 the temperature of the middle glass and T_2 the temperature of the inner glass.

The standard method for calculating the heat exchange coefficient of the glass surfaces facing the channel was replaced by a correlation based on the MacAdams formula: $h = C(\Delta T)^n$, where ΔT is in this case the temperature difference between air at the outlet and inlet of the ventilated channel. Based on the whole set of experimental data, the values of C and n were found to equal 3 and 1/3, respectively.

Calculation of long wave radiant exchange between the external glazed surface and the surroundings was initially based on the (inherent) assumption that the temperature of external surfaces exchanging long wave radiation with the window was equal to that of the ambient air. While this assumption may be justified in overcast or windy conditions, it might result in substantial errors in the sunny weather typical of Sde-Boqer, and for part of the time, Porto. Thermal images of the ground surface at Sde-Boqer, showing surface temperatures substantially warmer than ambient air temperature confirmed this hypothesis (Fig. 10). Since continuous measurement of surface temperatures was not available at any of the test sites, an empirical correction factor for the mean radiant temperature of the outdoor environment was calculated such that the errors in predicting the temperature of the external surface of the glazing were minimized. No correction was required for Cottbus, where conditions were generally windy and overcast, and the differences between air temperature and mean radiant temperature of the surroundings were small.

The revised model, incorporating the correlations derived from experimental data (in addition to the standard correlations for the rest of the system) resulted in predictions with an average error that is smaller than the error of the measured data. (i.e. $<1.5\,^{\circ}$C for each of the parameters predicted.) Sample graphs are shown in Fig. 11.

5. Discussion

The performance of the glazing system developed in the SOLVENT project may be evaluated against three criteria: its contribution to visual comfort, its contribution to the thermal comfort in the adjacent interior space, and its energy balance.

5.1. Visual comfort

The SOLVENT glazing system allows control over daylighting in buildings where large glazed areas would otherwise have resulted in excessive levels of illumination, or where the contrast between very bright glazed areas and relatively darker wall surfaces causes glare. Simulations with RADIANCE [22] of daylighting in a typical room with a window on one external wall show that compared with a clear-glazed window of similar size, the use of tinted glass in the SOLVENT window results in reduced levels of illumination. In sunny climates where interior illumination levels near a clear window may be as high as 30,000 lx, the SOLVENT window thus has a definite benefit, as indicated by lower values of the daylight glare index (DGI). The DGI is defined as [23]:

$$\mathrm{DGI} = \frac{2}{3}(\mathrm{GI} + 14) \quad (5)$$

where GI represents the glare index:

$$\mathrm{GI} = 10 \log_{10}\left(KP\frac{L_{\mathrm{S}}^{1.6}\omega^{0.8}}{L_{\mathrm{b}}}\right) \quad (5a)$$

where K is a constant depending on the units employed; P a “position factor” depending on the position of the source

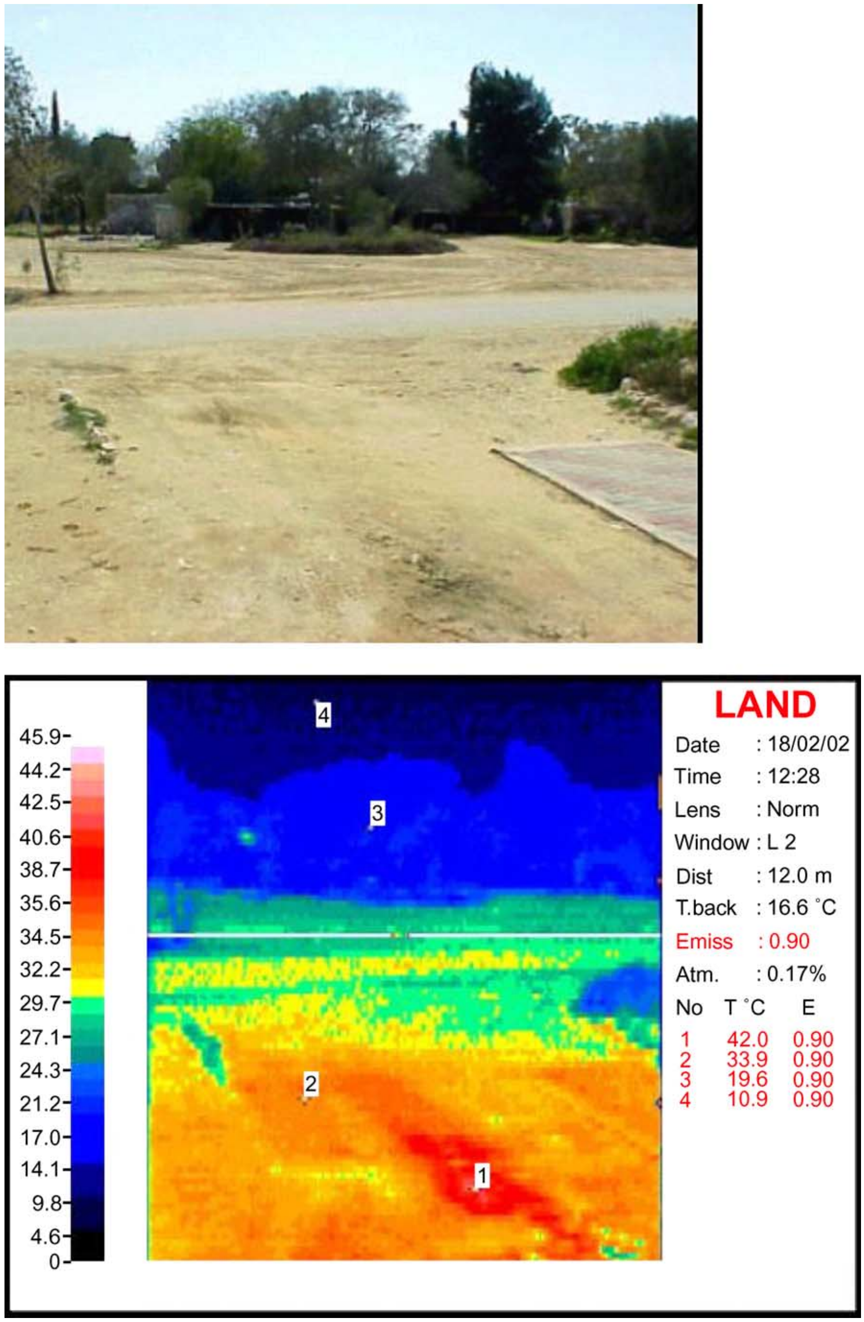

Fig. 10. The radiant temperature of the environment facing the window outside the Sde-Boqer test facility on a sunny winter day. The thermal image (right) shows a relatively warm soil (Points 1 and 2, with temperatures of 42.0 and 33.9 °C), and cooler trees (Point 3, 19.6 °C) and sky (Point 4, 10.9 °C). The average temperature of the camera's field of view was 26.8 °C, while air temperature was 16.6 °C.

with respect to the line of sight; L_S the luminance of the source; L_b is the field luminance; ω is the solid angle subtended by the source. DGI values of <16 correspond to imperceptible glare, values >28 indicate that glare is intolerable, and intermediate values characterize varying levels of glare.

Fig. 12 shows the DGI values for a viewpoint inside an office with two external windows on the same wall, as a function of the view direction and of the type of glazing used in the window.

5.2. Thermal comfort

Thermal comfort near large glazed areas is affected to a great extent by radiative heat exchange. In sunny conditions, the combination of a room air temperature of about 20 °C and direct solar radiation may result in mean radiant temperatures in excess of 45 °C. The SOLVENT window can absorb a substantial proportion of the incoming solar radiation: Experiments showed that in sunny conditions (solar radiation on the plane of the window in excess of 800 W/m^2),

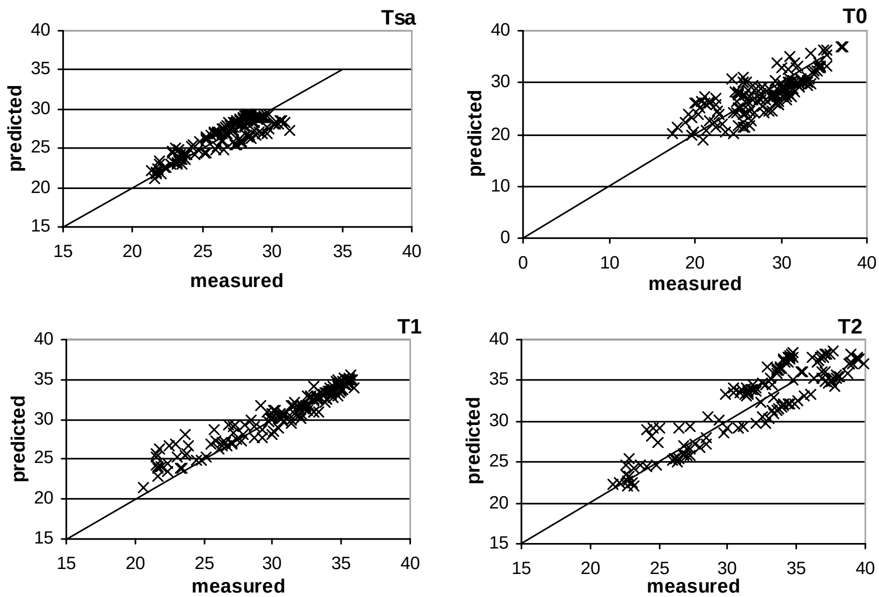

Fig. 11. Accuracy of predicted temperatures for Porto, Winter configuration, Gap = 44 mm. T_{sa} is the temperature at the outlet of the air channel; T_0, T_1 and T_2 are the temperatures of the external clear glass, the internal clear glass and the tinted glass, respectively. (Environmental mean radiant temperature set to equal air temperature + 30 °C; surface heat exchange coefficient $h_c = 3\Delta T^{1/3}$; $V = 0.76v(f)$; Error = 4.332).

the temperature of the tinted glass might be as high as 50 °C if the glass-to-glass width of the air channel was less than about 30 mm, restricting air flow between the two glazing components. However, the temperature recorded by a black globe thermometer suspended 1 m from the center of the SOLVENT window was substantially lower than that measured in the same manner in a space with an otherwise similar clear-glazed window (Fig. 13).

5.3. Energy balance

The SOLVENT window was designed to improve visual and thermal comfort in sunny conditions—"without compromising overall energy performance" in winter or summer. Detailed measurements were conducted at the PASLINK test cell in Cottbus equipped with a SOLVENT window, as follows: clear glazing – an 'SGG Planitherm Solar' window (double-glazed with low e-coating); absorptive component – a 5 mm "SGG Parsol grey" glass with a visual transmittance of $\tau = 0.5$. Seasonal differences in the solar transmittance were achieved by rotating the tinted glazing to the appropriate orientation: internal (winter), or external (summer). The heat transfer coefficient of the window was evaluated by two methods: (a) a center-of-glass value was obtained by direct measurement with heat flux and temperature sensors; and (b) energy balance calculations carried out for the whole test cell according to the standard PASLINK test procedure [15], which resulted in the following characterization of the glazing system (Table 2):

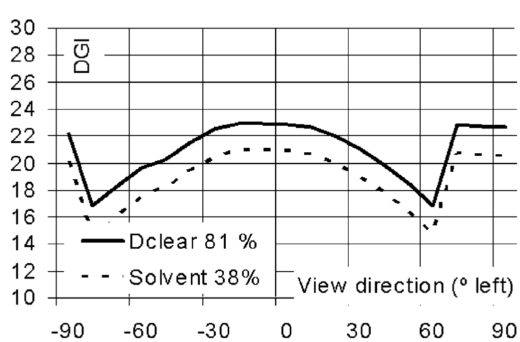

Fig. 12. Analysis of daylight quality in a typical office room with windows on one wall, under typical sunny conditions in Porto. Higher values of the daylight glare index (DGI) correspond to greater visual discomfort. Glare becomes perceptible for DGI values around 16 and uncomfortable for DGI values near 22–24.

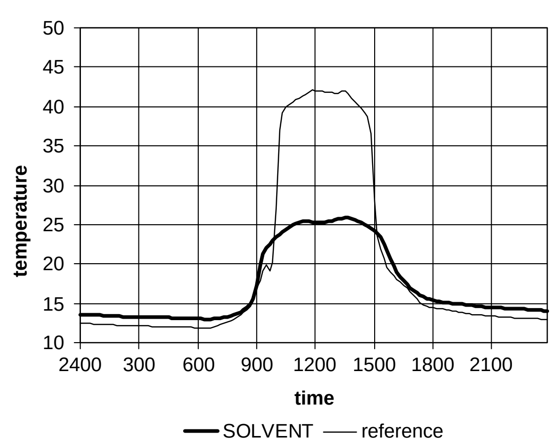

Fig. 13. Comparison of black globe temperature (°C) suspended 1 m from the center of the SOLVENT window and of a clear-glazed reference (Sde Boqer, 3 February 2002).

Table 2
Energy characteristics of the SOLVENT glazing system tested at the PASLINK cell in Cottbus

	Summer	Winter
Heat transfer coefficient (*U*-value, W/m^2 K)	1.1	1.1
Solar transmittance (*g*-value)		
With 20 mm gap	0.36	0.56
With 30 mm gap	0.36	0.59
With 50 mm gap	0.36	0.68

Energy loss through the glazing system is slightly higher than through a comparable window with an identical total thermal transmissivity, since the temperature of the air near the SOLVENT window is likely to be higher during sunny periods. In cold climates, the aerodynamic design of the ventilated channel, and in particular selection of an appropriate gap width, should thus be driven by the desire to allow warm air to be convected into the adjacent interior space. If the air flow between the clear glazing and the absorptive glass is obstructed, the total solar heat gain factor of the system may be reduced by up to 20%. The selection of a clear glazing with a low heat transfer coefficient has great importance, and low e-coatings are probably essential. In the summer configuration, the gap width had a smaller effect on the g-value, since in this mode energy transfer to the interior was determined mainly by the optical properties of the glazings.

An illustration of the partitioning of solar radiation incident on a SOLVENT window is shown for the window installed in the PASLINK test cell in Porto, with an air gap of 44 mm (Figs. 14 and 15). Having determined the convection coefficients, thermal balance equations for each surface allow calculation of the energy flow by each mechanism. The proportion of energy convected to the channel air was found to be about the same, or slightly less than the proportion of energy delivered to the interior by convection at the interior surface of the tinted glass and by long wave radiation from it.

The solar factor of the window in the winter mode (i.e., the fraction of the solar energy incident that ends up trapped in the interior) is roughly 62%, a reduction of 17% compared with the clear double-glazed component of the window alone. The addition of a tinted glass to control daylighting and glare thus resulted in a penalty in terms of the energy performance of the glazing system as a whole in the *winter mode*. This could in turn be offset by energy savings

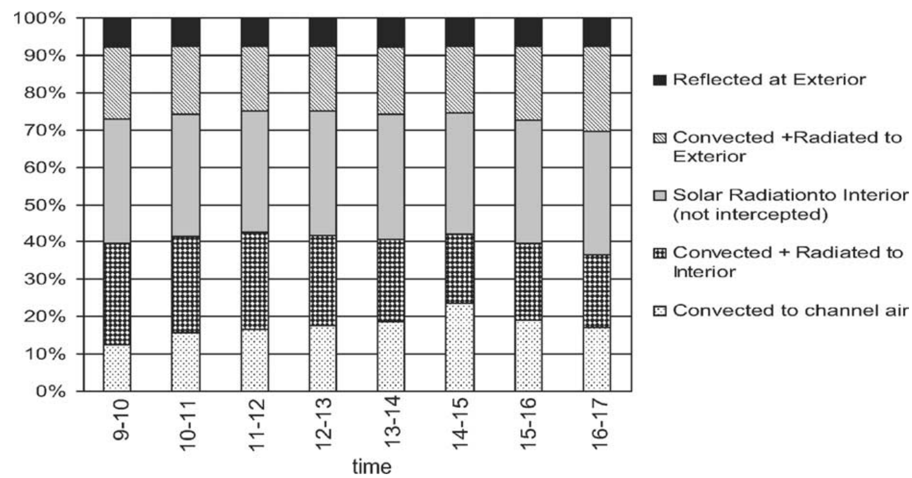

Fig. 14. Partition of the solar energy incident on the SOLVENT window at the Porto PASLINK test cell on a sunny day (9 November 2001). The window is in the winter mode, i.e. the tinted glass faces the interior.

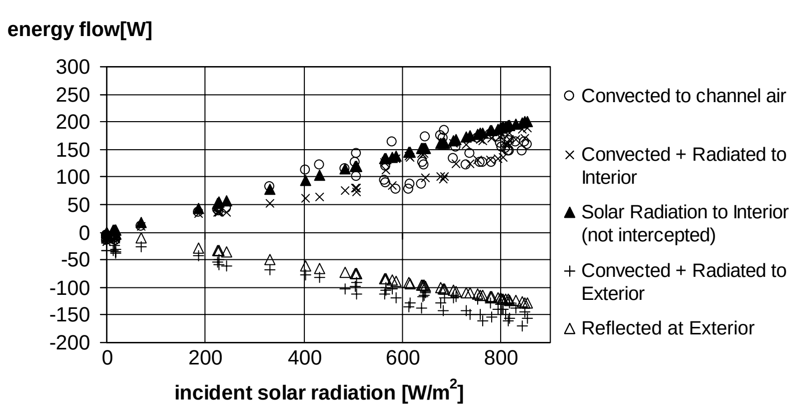

Fig. 15. Energy balance of the SOLVENT window in winter mode: example for Porto, 9 November 2002.

in the *summer mode*, and by lower electricity costs due to improved daylighting all year round, depending on the environmental conditions at each specific location. A detailed comparison of the year-round energy performance of the SOLVENT glazing system with other glazing systems was carried out as part of the SOLVENT project for typical offices, schools and residential buildings in different climates [24]. Results confirmed that the SOLVENT window decreases cooling energy demand substantially, while slightly increasing heating energy demand. The consequences of this behavior depend on the building and climate analyzed. For hot climates like Tel Aviv, where energy demand for cooling is much higher than energy demand for heating, the benefits of the SOLVENT window are substantial. In colder climates, such as Berlin, the penalty in terms of heating energy offsets the reduction in energy for cooling; the overall balance depends on building characteristics such as internal loads and set point temperatures, which may have an important effect on the ratio of heating requirements to cooling requirements.

6. Application

Application of the SOLVENT glazing concept required the resolution of two technical issues.

6.1. Development of a reversible frame

The SOLVENT glazing concept requires a fully reversible frame conforming to the following requirements:

- In *each* of the two opposing configurations, the glazing assembly incorporating the clear glass provides a weatherproof seal.
- The air gap between the two glazing assemblies is accessible for cleaning.
- The conversion of the glazing system, from winter to summer mode or vice versa, is simple and requires no special equipment.
- The surfaces of both glazing assemblies facing the air gap are smooth and create the minimum possible aerodynamic drag.

Two solutions have been proposed for frames conforming to the above requirements, and demonstration prototypes have been constructed (Fig. 16).

6.2. Design tools

The optical qualities and width of the ventilated channel of the SOLVENT glazing system must be specified in accordance with the specific environmental conditions found in different locations where it may be applied, and with the dimensions of the glazed area. A computerized tool was prepared to assist designers in the selection of an appropriate tinted glass, on the basis of daylighting considerations, and to assess the thermal performance of the resulting glazing system compared to a reference window.

Fig. 16. Two reversible frame solutions.

The SOLVENT Design Tool [25] has a simple WINDOWS Multi-document Interface. The user must first enter the required inputs by selecting appropriate clear and absorptive glazings from a WIS library and by specifying the geographic location (Fig. 17). The energy performance of the glazing system may then be simulated on an hourly, daily or monthly basis, for either the summer or winter modes. Each option appears in a separate sheet representing the particular window design being studied. The user may open simultaneously two or more case studies, simplifying comparison of results. The calculation engine in the design tool (written in ANSI C++) is identical to the one that was validated against the experimental results.

Concerning visual comfort analysis, the tool incorporates a library showing illumination levels in the room and daylight glare index (DGI) values for a set of different geometries, climates and glazing properties. For more case-specific analysis, a simple bash program was written to act as interface to the RADIANCE software and aids in obtaining

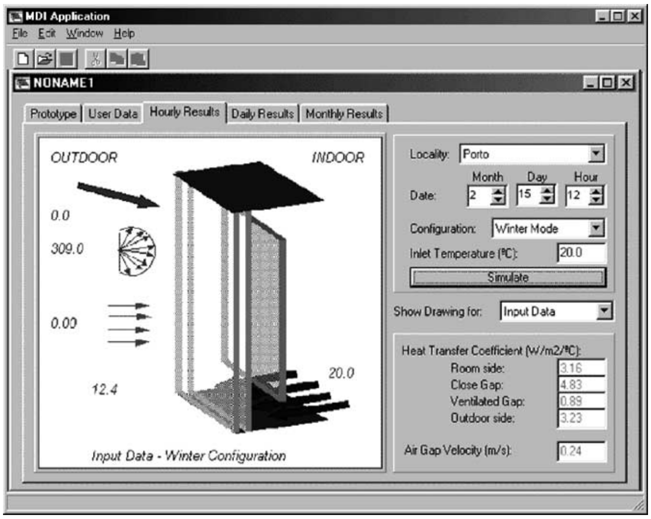

Fig. 17. Input screen of the thermodynamic analysis mode in the SOLVENT User Design Tool.

the illumination levels and DGI for user-defined cases with minimum input.

7. Conclusion

Compared with a conventional double-glazed window with similar optical properties, the SOLVENT glazing system has two main advantages:

(a) The fully rotatable frame provides building occupants with a flexible response for changing energy requirements, on a seasonal or even daily basis. The position of the tinted glass—facing indoors or outdoors—allows the occupant to either accept most of the solar radiation or to reject it. The operation of the rotating mechanism is simple, so this may be done in response to a short-lived heat wave, as well as to extended (seasonal) conditions. Furthermore, the performance of the glazing system is almost independent of orientation: The absorptivity of most tinted glazing is almost independent of incident angles, dropping off only at highly oblique angles (above 70°) where most radiation is reflected. Thus the glazing system may be applied with great benefit in situations where incoming solar radiation has a near-normal incidence and conventional shading devices are least effective—such as on windows facing east or west, or in any location where the diffuse and reflected components of incoming solar radiation are particularly high.

(b) The air flow in the ventilated channel helps dissipate solar energy absorbed in the tinted glass, which would otherwise be heated to uncomfortably high temperatures: even with the benefit of ventilation, the tinted glass in some configurations of the SOLVENT prototypes tested reached temperatures in excess of 50 °C on sunny days. In the winter mode, a much larger proportion of the incoming energy is converted to convective heat than would occur in a conventional double-glazed frame; In summer, energy dissipated by means of the ventilated channel results in a lower flux upon the clear-glazed element, reducing the solar heat gain substantially.

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References

[1] T.E. Johnson, Low-e Glazing Design Guide, Butterworth Architecture, Boston, 1991.
[2] M. Reim, A. Beck, W. Korner, R. Petricevic, M. Glora, M. Weth, T. Schliermann, J. Fricke, Ch. Schmidt, F.J. Potter, Highly insulating aerogel glazing for solar energy usage, Solar Energy 72/1 (2002) 21–29.
[3] D. Arasteh, R. Johnson, S. Selkowitz, Definition and use of a daylight 'coolness index', in: Proceedings of the International Daylighting Conference, ASHRAE, Atlanta, 1986.
[4] C.G. Granqvist, A. Azens, A. Hjelm, L. Kullman, G.A. Niklasson, D. Ronnow, M. Stromme Mattson, M. Veszelei, G. Vaivars, Recent advances in electrochromics for smart windows applications, Solar Energy 63/4 (1998) 199–216.
[5] R.D. Rauh, Electrochromic windows: an overview, Electrochimica Acta 44 (1999) 3165–3176.
[6] G.W. Mbise, D. Le Bellac, G.A. Niklasson, C.G. Granqvist, Angular selective window coatings: theory and experiments, Journal of Physics D: Applied Physics 30 (1997) 2103–2122.
[7] W. Lorenz, Design guidelines for a glazing with a seasonally dependent solar transmittance, Solar Energy 63/2 (1998) 79–96.
[8] K. Brandle, R.F. Boehm, Airflow windows: performance and applications, in: Proceedings of Thermal Performance of the Exterior Envelopes of Buildings II, ASHRAE/DOE Conference, ASHRAE SP38, 1982.
[9] J. Peck, T.L. Thompson, H.J. Kessler, Windows for accepting or rejecting solar heat gain, in: Proceedings of the Fifth National Passive Solar Conference, ISES—American Section, 1979, pp. 985–989.
[10] S. Medved, P. Novak, Heat transfer through a double pane window with an insulation screen open at the top, Energy and Buildings 28 (1998) 257–268.
[11] Y. Etzion, E. Erell, Controlling the transmission of radiant energy through windows: a novel ventilated reversible glazing system, Building & Environment 35 (2000) 433–444.
[12] J.L. Molina, I.R. Maestre, Thermal and optical modeling of complex glazing systems—Appendix 2 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.
[13] M. Sandberg, B. Moshfegh, H. Lundström, T. Törnström, Aerodynamic design and model development, Internal Report of the SOLVENT Project, The European Commission, Brussels, 2001.
[14] M. Sandberg, Final Aerodynamic Report—Appendix 1 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.
[15] H.A.L. van Dijk, The PASSYS test method to obtain thermal and solar characteristics of building components, in: Proceedings of the Third European Conference on Architecture, Florence, Italy, May 1993, pp. 84–87.
[16] E. Erell, Y. Etzion, S. Brunold, M. Rommel, V. Wittwer, A Passive Cooling Laboratory Building for Hot-Arid Zones, in: Proceedings of

the Third International Conference—Energy and Building in Mediterranean Area, Thessaloniki, Greece, 8–10 April 1992, pp. 117–124.
[17] V. Leal, M. Borges, E. Maldonado, Performance monitoring of the SOLVENT glazing system at Porto—Appendix 7 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.
[18] O. Gutschker, Performance monitoring of the SOLVENT glazing system at Cottbus— Appendix 8 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.
[19] Y. Etzion, E. Erell, W. Motzafi-Haller, Performance monitoring of the SOLVENT glazing system at Sde-Boqer—Appendix 9 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.
[20] F. Incropera, D. DeWitt, Fundamentals of Heat and Mass Transfer, John Wiley and Sons, 1996.
[21] V. Leal, M. Borges, E. Maldonado, On the Measurement of Temperatures—Appendix 4 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.
[22] G.W. Larson, R. Shakespeare, Rendering with Radiance—The Art and Science of Lighting Visualization, Morgan Kaufmann Publishers, Inc., 1998.
[23] N. Baker, A. Fanchiotti, K. Steemers (Eds.), Daylighting in Architecture—An European Reference Book, James & James, London, 1993.
[24] V. Leal, E. Maldonado, Whole building simulation—Appendix 11 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.
[25] I. Maestre, User Manual of the SOLVENT Design Tool—Appendix 13 to the Final Report of the SOLVENT Project, The European Commission, Brussels, 2002.